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THIRD ANNUAL MEETING

AD-487 155

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JOHN F. KENNEDY SPACE CENTER, NASA, COCOA BEACH,
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THE WORKING GROUP ON EXTRATERRESTRIAL RESOURCES

NOVEMBER 18/19/20, 1964

JOHN F. KENNEDY SPACE CENTER, NASA
COCOA BEACH, FLORIDA

Best
Available
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Photograph taken by Ranger VII spacecraft prior to its impact on the Moon at 6:25 A M PDT Viewed with the largest crater in the upper right hand corner, North is at the top of the photograph The picture was taken by the F-A camera with a 25 mm, F 1 lens from an altitude of about three miles some 2 3 seconds before impact The picture shows an area about one-and-two thirds miles on a side The smallest craters shown are approximately 30-feet in diameter and ten-feet deep There are many craters with rounded shoulders One rounded crater, at left toward the top of the photograph, is about 300-feet in diameter and has an angular rock mass in its center which might possibly be responsible for its origin Ranger is a project of the National Aeronautics and Space Administration and the Jet Propulsion Laboratory

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FOREWORD

The Working Group on Extraterrestrial Resources is composed of people from the National Aeronautics and Space Administration (NASA), the U.S. Air Force, the U.S. Navy, Office of Engineers of the U.S. Army, the Jet Propulsion Laboratory, and the Rand Corporation. It was organized for the following function:

> "To evaluate the feasibility and usefulness of the employment of extraterrestrial resources with the objective of reducing dependence of lunar and planetary exploration on terrestrial supplies; to advise cognizant agencies on requirements pertinent to these objectives, and to point out the implications affecting these goals."

MINUTES OF THE THIRD ANNUAL MEETING

The Third Annual Meeting of the Working Group on Extraterrestrial Resources was held at the Holiday Inn, Cocoa Beach, Florida, 18-20 November 1964. Attendees are listed in Appendix A. Condensed agenda followed was:

a. Subgroup reports

b. Welcome address

c. Plans for 1965

d. Technical papers

e. Election of officers

f. Banquet and after-dinner address

g. Tour of Kennedy Space Center

SUBGROUP REPORTS:

At the closed session the morning of the 18th, Dr. Ernst A. Steinhoff, Chairman of the Working Group, introduced the following Subgroup Chairmen who reported their Subgroup progress and plans:

Dr. John W. Salisbury, Chairman of the Subgroup on Environment and Resources;

Mr. Bruce Hall, Chairman of the Subgroup on Mining and Processing;

Mr. C. William Henderson, Chairman of the Subgroup on Logistics Requirements; and

Colonel Charles W. Craven, Chairman of the Subgroup on Biotechnology with Mr. James Malcolm. Mr. Malcolm will replace Colonel Craven as Chairman of the Subgroup for the coming year.

The program for next year was scheduled also for the closed session. Dr. Steinhoff, at the request of the Group, presented (instead of the "Program for Next Year") a paper on "Use of Extraterrestrial Resources to Advance Interplanetary Flight." He had presented this paper earlier in the week to the Third International Symposium on Bioastronautics and Space. It will be published in the Proceedings of that symposium.

WELCOME ADDRESS:

The Welcome Address was delivered to the full Working Group by Mr. Gordon Harris, Chief of Public Affairs, Kennedy Space Center, NASA.

KEYNOTE ADDRESS:

Dr. Steinhoff delivered the Keynote Address as "Objectives for 1965."

TECHNICAL PAPERS:

Messrs Henderson and Mitcham presented talks of topical interest on "Soviet Lunar Construction Potential." Technical papers presented are listed by Subgroup in Appendix B. Minor title changes may appear in the proceedings, but papers will be essentially unchanged in substance.

ELECTION OF OFFICERS:

At a meeting of the Steering Committee the evening of 18 November, the following officers were elected for the coming year:

WORKING GROUP	
Chairman	Dr. James B. Edson
Vice Chairman	Dr. John W. Salisbury
Secretary	To be chosen by Chairman
STEERING COMMITTEE	
Chairman	Dr. Ernst A. Steinhoff
Vice Chairman	Mr. James J. Gangler
Secretary	Mr. Ellis M. Bilbo

BANQUET:

The banquet was held at 2000 hours 19 November 1964 at the Holiday Inn. Officers were introduced, and the names of officers for the coming year were announced. Dr. Fred L. Whipple, Director Smithsonian Astrophysical Observatory, delivered the after-dinner address - "Evolution of the Solar System."

TOUR:

A tour of Cape Kennedy and Merritt Island was conducted 20 November 1964 by NASA. The last half of the tour was cancelled so that the Group might watch a launch of the Titan. The launch was cancelled.

REPORT OF THE ENVIRONMENT AND RESOURCES SUBGROUP

John W. Salisbury

It is clear that utilization of the lunar surface materials demands a detailed knowledge of their nature and composition. These two problems, therefore, are the principle ones which face the Environment and Resources Subgroup. Of these, composition, and the variation of composition over the surface, would appear to be the problem of greatest significance. Several members of the Subgroup are engaged in research designed to determine lunar composition and these efforts should be encouraged and, where possible, expanded. It should be noted here that the spot measurements of lunar composition that might be made by a Surveyor or Apollo vehicle are not what are required by the Working Group. Such measurements will neither tell us the composition of the lunar crust as a whole, nor will they give us any idea of the degree and kinds of compositional heterogeneities. Small compositional anomolies will probably present the most favorable opportunity for water extraction or for the extraction of any other lunar resource. Therefore, techniques to be used in identifying the composition of the lunar surface materials for the purposes of the Working Group should be techniques aimed at detecting range in composition and small differences in composition, rather than bulk averages. Some experiments may only need slight redesigning in order to meet this requirement and all experimentors on NASA vehicles should be made aware of the importance of detecting compositional anomolies on the lunar surface.

The nature of the lunar surface layer is as important as its composition to this Working Group. Base construction and other operations upon the lunar surface obviously depend upon detailed knowledge of the surface layer. Again, it should be pointed out that spot measurements from Surveyor or an Apollo landing vehicle are not sufficient to meet the needs of the Working Group, which might include far-flung exploration and the construction of remote field sites. Those experiments which may tie spot measurements together and make them meaningful in terms of the whole lunar surface should be actively advocated by the Working Group and accomplished by its members.

Other aspects of the lunar environment, such as radiation flux, micrometeoroid flux, and thermal parameters are necessary to life support and base construction activities. These parameters are better known at this time than those mentioned above, and it is anticipated that they will be thoroughly understood from experiments already planned or in progress. They are, therefore, not given priority in this statement of requirements, but only because we believe that there is no need to do so.

It is important for each member of the Working Group to remember that a thorough and detailed understanding of the lunar environment can be accomplished only by long years of manned and unmanned exploration. It is necessary to make this clear to the public and to the scientific community at every opportunity, so as to combat a general feeling that putting a man on the moon will solve all of our problems. If the importance of continuing scientific experiments is lost sight of now, critical data that we will need later in utilization of the moon will be lacking.

REPORT OF THE LOGISTICS REQUIREMENTS SUBGROUP

C. William Henderson

The Logistics Requirements Subgroup of the Working Group on Extraterrestrial Resources is a continuation and modification of the original subgroup for Facilities, Construction, Operation and Maintenance.

By November of 1963 the original subgroup, under the able chairmanship of Lt. Col. G.W.S. Johnson, had achieved a large percentage of its goals by recommending study areas that should be investigated in order to fully comprehend the requirements of lunar surface systems. In many cases these recommendations were later pursued by the NASA, Air Force, and Army.

With the resignation of Lt. Col. Johnson, this author was requested to chair the subgroup. At that time, it was decided that the subgroup had achieved its former goals and could best advance the efforts of the Working Group by broadening its fields of interest. Consequently, the Steering Committee charged the subgroup with the task of determining the real requirements (if any) for extraterrestrial resources and the practicability of their use. These requirements, in turn, could then be translated into recommendations of national expenditures for research programs oriented toward extraction and utilization of only those extraterrestrial resources adjudged practical and desirable. In light of this new task assignment, the subgroup name was changed to "Logistics Requirements".

In line with the new subgroup function, several activity areas were formulated and were formalized as committees with assigned chairman and members. The Committees and their functions are:

a. <u>Logistics Burden for Propellant Production:</u>

This committee will establish a reference logistics burden model for each of several potential propellant resources. These models will include a definition of required facilities, equipment, personnel and power to establish and operate production plants in extraterrestrial environments based upon an assumed state of the art and a specified production rate.

b. <u>Logistics Burden for Power Production:</u>

This committee will establish a reference logistics burden model for each of several potential extraterrestrial power resources. These models will include a definition of the required facilities, equipment, personnel and power to locate, tap and operate power plants utilizing extraterrestrial resources.

c. Logistics Burden for Facility Materials:

This committee will establish a reference logistics burden model for each of several extraterrestrial building materials. These models will include a definition of the required facilities, personnel equipment and power to extract, process and emplace facility materials derived from extraterrestrial sources.

d. Estimated Resource Demand:

This committee will estimate the potential demand of all proposed extraterrestrial resources and will establish the time phasing for each resource use. In addition, this committee will assign scaling factors to estimated reference logistics burdens to encompass varying time phases and production rates.

e. Logistics Analysis

This committee will establish the estimated launch vehicle availabilities and capabilities with respect to time and mission requirements. In addition this committee will compare the relative costs of delivering the logistics burden imposed by utilizing extraterrestrial resources to the costs of delivering the resources directly from Earth.

The subgroup as a whole will evaluate the work performed by each committee, and will recommend to the Working Group those uses of extraterrestrial resources which it believes warrants continued effort. It is anticipated that the desirability and practicability for utilizing many proposed extraterrestrial resources will not become apparent during the course of study due to unpredictable demands, availabilities and technical state of the art. In this event, the subgroup will recommend areas of further investigation required to supply this information.

The output to date of the Logistics Requirements subgroup has been confined principally toward internal organization and developing a procedural methodology. Consequently, this year's effort has resulted in an increased membership of personnel more closely associated with engineering disciplines and operations research. The basic accomplishments have been the establishment of intercommittee procedures and a method whereby practical requirements for extraterrestrial resources can be determined numerically once quantitative values for Logistics burdens are established.

It is difficult to foresee how much can be accomplished within the next year. We hope to pursue several additional areas of endeavor. Possible types of work to be performed are:

a. Apply the analytical methodology to the results now at hand related to hydrogen and oxygen from the lunar surface.

b. Continue propellant processing plant and equipment requirements for other planetary bodies.

c. Consider requirements for processing of resources on the lunar surface of construction materials and for electrical power.

We anticipate the work to progress rather slowly. This is due to the fact that the type of work our subgroup is doing has little or no government funding.

Most of the effort will have to be accomplished by the individuals on their own time. Of course, we will also attempt to encourage enthusiasm within the government and industry to provide funding for studies of this nature.

In fact, it behooves all members of the Working Group to espouse that officialdom study the practicability of utilizing extraterrestrial resources. This must be explored before any major lunar and planetary programs can be effectively planned and the consequent funding of any serious resource utilization research can be obtained. Today, even the pursuit of lunar and planetary exploration efforts of any proportion are in jeopardy, and may continue to be until the public and the legislators become acquainted with the desirability of such programs and their eventual impact on the advancement of mankind.

The following pages represent the achievements of several subgroup committees as reported by their chairmen.

A. COMMITTEE ON LOGISTICS BURDEN FOR PROPELLANT PRODUCTION

James J. Gangler

The Committee on Logistics Burden for Propellant Production was formed for the purpose of establishing a reference logistics burden model for each of several potential propellant resources. These models were to include a definition of required facilities, equipment, personnel, and power to establish and operate production plants in extraterrestrial environments based upon an assumed state of the art and a specified production rate.

The committee arbitrarily decided that for the first effort only oxygen and hydrogen would be considered for propellant production. Furthermore, two indigenous resources for these propellants would be assumed:

1. Silicate rock for oxygen (in this case, hydrogen, the other required propellant would be shipped to the moon from earth) and

2. A hydrated mineral, e.g., chrysotile, having a recoverable water content of ten weight percent.

The problems were outlined and assigned to the committee members as shown in Table A. All members have completed their various assignments, and individual reports have been submitted. These are listed in Table B. It is intended that the Committee for the Comparison of Extraterrestrial Resources versus Earth Resources will use this information and data in pursuit of their studies.

Next year's activities of this committee will be along the lines of refining the information in the reports listed in Table B as it is needed by the Committees of the Subgroup.

Table A

OUTLINE OF OXYGEN AND HYDROGEN PRODUCTION PROCESSES

1. Oxygen Production	2. Oxygen & Hydrogen Production from 10% Water Bearing Hydrate	Contributor*	
a) Mining (from deposits of 3 to 500 feet deep)	a) Mining	Hayward	
b) Transportation (assume one mile from working face to plant)	b) Transportation (assume one mile from working face to plant)	Hayward	
c) Comminution (coarse)	c) Comminution (fine particles)	Hayward	
d) Retort	d) Fluidize bed	Rosenberg (1) and Glaser (2)	-Facilities -Equipment
e) Chemical Processing	e) Condenser	Rosenberg (1) and Glaser (2)	-Power -Personnel
f) Electrolysis (assume a rate of 9 lbs. H_2O/hour)	f) Electrolysis (assume a rate of 9 lbs. H_2O/hour)	Rosenberg and Glaser	
g) Liquefaction (oxygen)	g) Liquefaction (oxygen and hydrogen)	Glaser	
h) Storage	h) Storage	Glaser	

* Barney to make contribution to any element.

Table B

List of Reports Prepared
by the Committee on Logistics
Burden for Propellant Production

1. "A Preliminary Logistics Burden Model for the Production of Lunar Ores" by Carl B. Hayward, North American Aviation, Downey, California

2. "Requirements for On-Site Manufacture of Propellant Oxygen from Lunar Raw Materials" by S.D. Rosenberg, G.A. Guter, and M. Rothenberg, Aerojet-General Corporation, Azusa, California

3. "Fluidized Bed Systems" by Peter Glaser, Arthur D. Little, Inc., Cambridge, Massachusetts

   "Electrolyzers for Use on the Moon" by Peter Glaser, Arthur D. Little, Inc., Cambridge, Massachusetts

   "Cryogenic Storage on the Moon" by Peter Glaser, Arthur D. Little, Inc., Cambridge, Massachusetts

   "Liquefaction of Hydrogen and Oxygen" by Peter Glaser, Arthur D. Little, Inc., Cambridge, Massachusetts

4. "A Design Criterion for Lunar Propellant Manufacture" by D.M. Cole and R. Segal, General Electric Company, Pennsylvania

NOTE: The text of these reports are not included in this report because their content is a part of the published papers presented by the authors at the 1964 Annual Meeting of the Working Group.

B. COMMITTEE ON LOGISTICS BURDEN FOR FACILITY MATERIALS

Donald W. Butler

This committee was organized within the Subgroups to determine the potential desirability for extraterrestrial resources as a material for facilities construction and to establish the practicality of their use. Although most of the other committees in the Subgroup have some areas of interest in all space missions, this committee by definition will be concerned only with construction of facilities on terrestrial-type surfaces. In the foreseeable future, therefore, this committee will be concerned with lunar exploration systems and their facility requirements.

A program of investigation has been formulated which we feel will be purposeful and continuing and which, if continued on a year-to-year basis, can serve to be a standard reference and guide to further research and study. The program outline is as follows:

a. Identify all lunar exploration systems; those which are programmed and under study; and those which can be projected as follow-on systems against increasing mission requirements and sophistication.

b. Identify the facility requirements for each of these lunar exploration systems.

c. Classify and catalog all terrestrial material requirements for all facility systems identified in b. above, identify the projected source and the processing system utilized.

d. Identify and catalog all program-designated lunar materials required in facility systems, for example lunar soil for shielding purposes. Identify possible processing techniques for such program-designated lunar resources which would improve the effectiveness of such material for the use intended.

e. Identify possible lunar materials which, by means of a processing technique, can be utilized and substituted for program-designated terrestrial material.

f. Identify possible lunar materials which, by means of a processing technique, can be utilized in new and novel applications in advanced lunar exploration facility systems.

g. Identify the logistics burden models associated with the processing of such lunar materials and the application procedure of the refined product. The model for each material will include a definition of the required facilities, personnel, equipment and power to extract, process and emplace facility materials derived from extraterrestrial sources.

It will take some indefinite period of time before a group is organized and functioning on a continuing basis on this overall problem. It is our intention to expand the membership of the committee to a sufficient number and a sufficient diversity of technical capabilities to investigate all aspects of the program. To this end, a group of industrial corporations and university research institutes have been queried concerning participation on the committee in carrying out such a program. The response has been enthusiastic and the personnel suggested represent a good spectrum of the scientific capabilities necessary to carryout the program.

We look for real progress to be made in the coming year to implement this program. We also expect to have individually prepared papers on subjects directly pertinent to the program goals next year.

C. COMMITTEE ON LOGISTICS BURDEN FOR POWER PRODUCTION

Shelton S. Alexander

1. Summary

Preliminary consideration of utilizing natural lunar resources to supply large amounts of power (100KW) for sustained lunar base operations has led to the following conclusions:

1 Few types of natural resources would be capable of supplying the required power, even with improved energy conversion devices. Those showing promise include power recovery from lava pools (Ref. 1), isotope "batteries" using isotopes extracted from lunar surface (Ref. 2), solar energy provided efficient conversion and power storage can be effected, and possibly fuel cells using indigenous hydrogen and oxygen (water).

2 Combined use of natural resources and nuclear energy looks promising for power requirements in the megawatt range. Controlled detonation of nuclear bombs in an underground cavity can yield large amounts of power (megawatts) relatively inexpensively with a simple recovery system (Ref. 3). Moreover the energy may be increased by a factor of 1,000 at only double the cost.

Such a system has the further very important advantage that the detonations can be used as seismic sources for detailed investigation of the interior of the moon.

3 Drilling and/or mining operations probably will be essential in producing or preparing to produce sustained power using natural resources.

2. Recommendations

1 Investigate in more detail the feasibility of recovering power from the natural sources listed above, including cost and probability of occurrence of the resource as parameters.

2 Perform terrestrial field experiments to test proposed power systems whenever possible, e.g., lava pools, controlled underground explosions.

3 Develop more efficient energy conversion devices, especially those for thermal energy conversion.

4 Investigate the possibility of using naturally occurring elements in chemical reactions to provide energy.

5 Study means of efficiently transporting power from point to point on the moon in order to supply expeditions or outposts and reduce their independent power requirements.

3. Future Work

During the coming year the Power Production Committee will devote most of its attention to items 1,4, and 5 in the above list of recommendations. Hopefully item 2 will be the natural result of these more detailed feasibility studies.

References

1. Kennedy, G.C. and Griggs, D.T., "Power Recovery from the Kilauea Iki Lava Pool", Report RM-2696-AEC, The Rand Corporation, 1960.
2. Huth, J.H., "Power in Space", Report P-1389, The Rand Corporation, 195.
3. LaBounty, R.H., "A Lunar Power System", Astro 352 Report, Air Force Institute of Technology, 1964.

REPORT OF THE MINING AND PROCESSING SUBGROUP

Bruce M. Hall

In the 1963-64 year the M&P subgroup reorganized into three operating committees. These were "Identification of Lunar Resources," Jack Green, Chairman; "Identification of Ores or Source Materials from which the Necessary Elements or Compounds Could Feasibly and Economically be Extracted and the Mining Procedures Required," M. A. Klugman, Chairman; and "Bibliographic Research," Peter Glaser, Chairman. Emphasis was placed on a broader spectrum of resources than the prior year. This necessitated a more general approach to the problem of ore production and processing. (See minutes of 8 April meeting.) Future studies will attempt to establish a priority listing of resources based on need, probability of occurence and practicality of production under restraints of lunar mining and processing.

The committee on "Identification of Lunar Resources" recommends that the following problem areas receive initial consideration:

1 What resources can be identified by active or passive techniques?
2 What resources are amenable to detections using yes/no techniques?
3 What resources will be easy to find with or without instruments? By manned or unmanned probes? Or mobile or immobile probes?
4 What are the six most important resources to detect in the following time periods for a moon that is 95% impacted?

Now
1965-68
1968-72
1972-78
1978-90
Beyond 1990

5 As above for a predominantly volcanic moon?
6 Are some exotic "resources" such as lunar bacteria worthy of study?
7 How long can ice or permafrost exist in caves or subsurface under lunar conditions?
8 Do we need to study the genesis of lava tubes?
9 What might be the alteration pattern around lunar fumaroles in general?
10 What happens to the 10% by weight of water when a carbonaceous chondrite impacts on the dark or the light side of the moon? Are there optimum terrain situations involving dust that would retain some of this water in shadow?

The committee on "Identification of Ores . . . " recommends the following research activities:

1 Literature survey on processing methods, both preparatory and extractive.
2 Operation of underground mining under simulated moon conditions.
3 Operation of extractive processes under simulated moon conditions.
4 Investigation of plasma torch techniques.
5 Investigation of blasting in a vacuum.
6 Various drilling methods in a vacuum with emphasis on temperature rise versus cooling methods, and removal of cuttings.
7 Control of atmosphere underground with emphasis on sources, corrosiveness, migration through rock types, and possible coatings to control gas leakage.

REPORT OF THE BIOTECHNOLOGY SUBGROUP

Charles W. Craven

There are two of us here today that have kept up with the biotechnology activities during the past year. Mr. Malcolm and myself. We have had meetings and activities going all year and think that we have found some things of interest to the group as a whole. Our subgroup includes Mr. Dole, Mr. Thompson, and Dr. Lindberg. Surprisingly, we early learned that Extraterrestrial Resources, as such, was not of much interest to the biomedical or bioastronautics community. I am not sure just why this is the case. However, it seems that these people are so concerned with immediate problems, i.e., the Gemini flights and the Apollo program that they can't see any advantage to expending energy and resources for our Extraterrestrial Resources activities. There may be an improvement next year. We have detected just a little bit of interest.

During the past year we have spent our time in reviewing the state-of-the-art in several fields. Namely, (1) life-support systems and optimum trade-offs for closed environments, (2) nutritional problems such as you might expect with a lunar base for an observatory, and (3) extraterrestrial suits. During the presentation of our reports tomorrow afternoon, we will point out several fruitful areas for research work that are adaptable to ground based simulator studies. We think that such simulator studies are of great importance to the group's activities. Thus the bioastronautics research talent might become more long range in nature and get a bit ahead of the day-to-day problems. This was the case about four years ago when considerable long range research was in progress, i.e., studies of life under a simulated Mars environment as influenced by Dr. Strughold at the Aeromedical Space Division, Brooks Air Force Base. We feel that additional work should be done on algae systems, physico-chemical oxygen regenerative systems, Hydroponic techniques, and refinement and test of a hard suit suitable for extra-vehicular exploration.

It would be valuable to the lunar program for our group to outline a series of tasks and observations that the astronauts might carry out on the lunar surface, tasks that the lunar observer could better complete than might be expected from an automated mechanical system.

Mr. Malcolm, a very helpful co-chairman has some things to report.

MALCOLM

As Colonel Craven pointed out, the field of biotechnology may be unique in that there is a great deal of current activity stimulated by the problems of today in Gemini and Apollo. However one of the problems to which the subgroup will address itself in the coming year, will be to point out where the requirements for exploitation of extraterrestrial resources,

insofar as biotechnology is concerned, differs somewhat from those requirements reflected in todays problem, Gemini and Apollo. We think that by pointing these things out, we will be able to stimulate more interest in the people that have the background to really attack the basic problems that are involved.

One area that we will look into will be advanced research, the algal system for example, would fall in the general area of advanced research. In other words, advanced systems which could be applied to extraterrestrial environment, particularly land based environments, the moon and on other planets. We believe that by careful deliberation of our subgroup, and by stating the problems in a clear and basic fashion, we will be able to stimulate the imaginations of the community as a whole, and that of biotechnology, toward developing a successful attack on the solution of these problems. So one of the first things we want to do, is to carefully define the problem in the light of requirements for extraterrestrial resource exploitation.

I might point out here, that insofar as biotechnology is concerned, one of our basic resources is man. We have also defined our resources, not only as being those which we might find in an extraterrestrial land base but also those things which are by-products of man's existence, in other words, we would include, for example, algal production of food and processes for recovery and reuse of all human wastes to the maximum extent.

In addition to the advanced research area, we have a short range objective. Before the time of algal farms, certainly the first manned lunar operations will concern processes that we would define as near time frames. Even here, although there is much work under-way, in laboratory demonstrations and in association with study of lunar exploration planning, we cannot select processes from the drafting board because we do not know reliabilities. The details involved will be covered in the papers presented tomorrow.

There are areas in which we can stimulate interest in terrestrial demonstrations, to show the degree of reliability in the specific processes in biosupport technology. To do this, we will employ, or we hope to employ, several techniques. Where we have particularly specialized and qualified participants in the group, these participants may undertake specific investigations in particular fields of interest. We would also hope to stimulate open meetings with workers in the community at large, including industrial participants, in which we would discuss the problems involved in both the near time frame and the advanced research phases of biotechnological support. We hope in the next year, specifically, to develop what might be called a problem statement, or, perhaps, a research and development guide book, one in which we would define clearly the various problems that might be met in connection with extraterrestrial resources development.

Another specific goal would be to formally collate the findings of our evaluations in the past two-year period, so that by this time next year, we might have a more formal report to present on the state-of-the-art. One that would more comprehensively cover the field than we have been able to do in the papers that will be presented tomorrow.

In view of the objectives that we have set, we can anticipate some expansion of our committee membership. As Colonel Craven indicated, our numbers, up till now, have been relatively few, particularly in contrast with the membership in the other subgroups, we will make a specific endeavor to solicit the help of other people having responsibilities and interests in the field of biotechnology, and we hope, thereby, to make a fairly remarkable measurement of our "velocity on the horizon" by this time next year.

CRAVEN

I have a few more remarks here, Dr. Steinhoff. Some of this will tend to come out after our presentation tomorrow afternoon but to state again some of the things that Mr. Malcolm has brought up, we feel that this is a group you cannot ignore, and that all of us can make a worthwhile contribution to the National Space Program by keeping the Biotechnology Subgroup in your group. We also feel that it should be kept more or less separated but not splintered off into the biomedical field of endeavor.

We have noticed, in our year's activities of more or less defining this problem some areas that we think could be highlighted and maybe as a whole the Extraterrestrial Working Group could bring some pressure to bear or influence others to get on with the job. For instance in the hard suit, this lunar type suit, we believe that this is a device or technique that could be used in the Apollo program. Another area of immediate application is that of trace contaminates for people living in a closed environment for a long period of time. This is very adaptable to ground based simulator. No one has really worked on this area for long periods, i.e., had people living for six months in a closed environment. We think it is time to set up a lab that can produce a year's resources, maybe algal units where you actually use the products to feed human beings. We found that in spite of all the literature we have on nutrition, no one has really gone into the problem of feeding people food just as an energy and body keeping element. It is so warped and influenced by people's emotions. For instance each of us is an expert in what is good to eat. We do not really, as a group, recommend that someone set up a lunar base on earth, but I believe that after another year or two, work in this field will show how this might be a very useful thing to do.

PLANS FOR 1965

Ernst A. Steinhoff

In its over 3½ years of activity, the Working Group on Extraterrestrial Resources has come a long way towards the objective to show that utilization of Extraterrestrial Resources may eventually become an important stepping stone for the advancement of spaceflight. To progressively reduce the cost of spaceflight operations to remote goals and to increase its safety of operations by creating increasing self-sufficiency of remote lunar or later also planetary bases should be a worthwhile goal. While our objectives of the past years were to determine some of the items of Logistics of Spaceflight which very probably can be obtained earliest at Extraterrestrial locations, thereby gradually reducing the logistics burden otherwise carried by space supply vehicles.

The three most active subgroups of the Working Group have built up a host of background material to clarify their objectives and to describe the tools at their hands to achieve these objectives. As in all human, and particularly scientific group efforts, the success of our effort depends on the leadership of those who spearhead these efforts and the degree of motivation this leadership is able to convey to and create within the membership of their teams. It is gratifying to see that in these past years this has been achieved to an increasing extent. In spite of the fact that it is a voluntary working group depending solely on the motivation of its individual members who come from government laboratories and offices as well as non-profit corporations and its associate members coming from industry and universities, the contributions have grown in volume as well as in depth. One of the major reasons for this growth is that the organization to which individual members or associate members belong have supported these members and have sent some of their representatives to the meetings of the subgroups, the bodies in which the real work of the working group is done. Many of our members have, and are, participating in policy-making functions, or are providing guidance and advice, in those areas which are directly devoted to increasing self-sufficiency, safety, reliability and improvement of Logistics of Spaceflight. In the past year, great progress has been accomplished in areas in which our imagination could shape and stimulate the individual steps towards the solution of Extraterrestrial Logistics into models and matrices, showing interdependence of functions and critical path situations. In many areas our colleagues have been able to identify parameters and operational necessities which enabled them to separate less promising avenues from those which would facilitate achieving their goals. Even the first rudiments of cost effectiveness or energy utilization effectiveness of the various approaches appear and are bound to increase in depth and value. In many areas of endeavour, however, inputs are lacking concerning more concerted efforts in our lunar and planetary probe programs. To obtain these would make our efforts more meaningful, and reduce the number of choices to be considered in the variety of our conceptional models. More emphasis is also needed to improve methods permitting acquisition of such data from observations directly from earth, from earth orbit and from fly-by vehicles. Closer relations of our various subgroups with

corresponding elements of the National Science Foundation and increased mutual feedback would definitely aid in filling many knowledge voids or could lead to efforts methodically reducing existing gaps. One of the areas in which this need of a closer working relationship exists, is covered by the Subgroup on Environment and Resources, headed by Dr. John W. Salisbury of the Air Force Cambridge Research Laboratories. His Working Group has been one of the most effective and active ones, owing to his relentless efforts and his inspiring leadership. I would like to quote verbatim the closing paragraph of the objectives of this subgroup for the coming year:

"It is important for each member of the Working Group to remember that a thorough and detailed understanding of the lunar environment can be accomplished only by long years of manned and unmanned exploration. It is necessary to make this clear to the public and to the scientific community at every opportunity, so as to combat a general feeling that putting a man on the moon will solve all of our problems. If the importance of continuing scientific experiments is lost sight of now, critical data that we will need later in utilization of the moon will be lacking."

I would like to expand John's remarks to include the entire scientific community which is working on the planning and execution of the U.S. Lunar program.

The next subgroup, headed by Bruce M. Hall of the Office of the Chief of the Army Engineers, is devoted to the subject of "Mining and Processing." Many of their conclusions parallel these of John Salisbury's subgroup. While the previous years work was devoted to review the broad spectrum of resources and aimed towards a more general approach to the problem of ore production and processing, the coming year's objective will be to establish a priority listing of resources based on need, probability of occurrence, and practicality of production under restraints of lunar mining and processing. The subgroup will attempt to narrow down its study goals to the identification of those processing methods which can be used under lunar environmental conditions in the most economic manner as to manpower requirement and electrical energy use. Feasibility and economy of ore extraction is another area which will require further narrowing down to identify the most promising avenues of further endeavor. Bruce Hall is supported by Jack Green, M. A. Klugman, and Peter Glaser.

The Logistics Requirements Subgroup, headed by C. William Henderson of NASA Headquarters, has devoted its efforts to the identification and clarification of requirements for various major areas of logistics.

After evaluation, these can be translated into recommendations for national expenditures for research programs oriented toward extraction and utilization of only those Extraterrestrial Resources adjudged practical and desirable. "Bill" Henderson during the past year has broken down his subgroup into five committees. Three of the committees deal with the determination of the Logistics Burden for these major support areas:

a. Fuels and Propellants

b. Extraterrestrial Power Sources and Production

c. Facilities Materials, Support Manpower and Power Requirements

A fourth committee deals with the entire demand for resources and the proposed time phasing for the utilization of each resource. Scaling factors then will be able to adjust the Logistics Burden to reflect varying time phasing and production rates for each of the above quoted burden areas.

These numbers again will be adjusted to the estimated launch vehicle availability and capability with respect to time and mission requirement, by a fifth committee. Following this then a cost effectiveness study should permit a comparison between the relative cost of delivering the Logistics Burden from Extraterrestrial Resources and direct delivery of the supply from earth.

An evaluation of the results of the studies of these five committees then will be performed by the subgroup, and recommendations will be formulated to the Working Group Steering Committee to adjust the study objectives and recommendations between steering committee and subgroups and vice versa will lead to a constant realignment of the optimum solutions as far as time, launch vehicle capability and knowledge of environmental information is concerned.

The fourth subgroup "Bioastronautics" was active during the past year. Its chairman, Colonel C.W. Craven, due to his duties at SSD, will not be able to continue chairmanship and Mr. Malcolm, who in the past already substituted for Colonel Craven, has been elected chairman of the subgroup for the coming year. Our thanks to Colonel Craven for his past efforts and best wishes for his further career. Since the annual report and its recommendations for future work were not at hand at this writing, I will only make some general remarks concerning this subgroup. Its particular attention should be on the evaluation of maturing life support equipment, its adaptability to use Extraterrestrial Resources for resupply, and the changes necessary to accommodate 30 to 900 days of unattended operation (except for replacement of leakage losses and replenishment of such chemicals which cannot be regenerated economically). Definition of radiation protection requirements and solutions for missions from 90 to 900 days should also find close attention by the subgroup. It is expected that with the advent of operating, transport option, manufacturing cost and resource demand models, together with cost effectiveness models, the inputs of bioastronautics become more important and may well permit alternate choices of approach. It is hoped that Mr. Malcolm will be able to establish closer contact and working relation with the other subgroups and so create feedbacks, important for the other three subgroups and the Steering Committee.

As you will have concluded from the subgroup chairman's annual reports, there has already been a considerable narrowing of objectives as compared to earlier annual meetings. More specific recommendations are beginning to appear, which will be increasingly reflected in research objectives of our space programs. This trend will continue and will be increasingly adjusted by feedbacks from our foreseeable national launch vehicle programs. The expanding use of models, as exemplified by Bill Henderson's Report, which in my opinion is an excellent one and should set an example for the quality and

depth of the reports of all subgroups for the next year, will have its influence in improving cross subgroup communications. In competing groups one group is usually superior to the others and so provides a challenge for the others to do equally well or better next time. My congratulations to Bill for a job well done!

At this point and time, I would like to call your attention to the fact that the space-flight model for the case of all resources being supplied from earth is within the current state of the art optimized by the Saturn C-5 technology and possible further advances beyond the Saturn C-5. A logistics scheme using C-5 vehicles and their derivatives in my judgment would not be optimum as to the layout and performance of the transport means based on use of Extraterrestrial Resources. Many objectives can currently be achieved only by using multi-staged vehicles, of which a part is irrecoverably lost, thus increasing the cost, as compared to a transportation scheme in which vehicle hardware losses due to staging are minimized or eliminated altogether. Current studies as the 10-passenger orbital carrier of NASA, and others, deal with the usefulness merits and economic trends of recoverable earth to orbit transportation systems. These open the possibility that as time goes on, more and more of our space transportation systems will be recovered and will have to be designed for re-usability. This trend will be reflected first in subsystems development trends and later in the development trend and operating modes of entire transportation systems. For space transportation systems which can refuel at both ends of their journeys, the terminals very probably will be orbiting terminals, a future growth form of our planned orbiting space stations. Proper design can lead to the reduction in stage numbers used and to the design and development of single-stage modules. These then can bridge the gap between Earth orbit and Moon orbit and in a modified form between Earth orbit and Mars orbit. For favorable constellations between Mars and Earth there is no greater Δv requirement than that needed to bridge the gap between Earth and Moon orbits. These single-stage modules will then be truly recoverable and reusable. It is apparent that this modification of the space traffic scheme will reflect back into the mathematical models as outlined by Bill Henderson and will give different results as those derived from a logistics scheme characteristic for the Saturn C-5 Technology class.

You all will realize that results of these more advanced logistic models will feed back into the vehicle design and the layout of the resulting space traffic scheme. It is not too late to provide a clear insight into the advantages to be gained by the design of an Extraterrestrial support system as well as the actual transport vehicles required to meet such an objective. The work of the coming year should start to reflect this potential trend and should find answers wherever these are affecting the space transportation system planning or vehicle design.

I am certain that this trend will accelerate in the year following the work and studies of the Working Group in 1965 and should be reflected in a growing number of research objectives to be pursued by the agencies involved in general interplanetary flight, Earth orbital flight and selection of earth to orbit and moon to lunar orbit transportation systems. Only constant up-dating of the develop- operational models will at all times provide the proper departure points for near research objectives. Here the more and more specific demand for environmental data of the Moon, the lunar surface, or lunar surface and composition anomalies, will effect the intensity as well as breadth of our observational efforts,

be these from the Earth surface, from satellite orbits or fly-by probes. I am certain that more specific data demand will increase for all of these activities and eventually will include similar demands for data of Mars and its Moons.

I was highly pleased to learn that Gerhard Schilling of Rand has recently published a note dealing with the orbit decay of phobos and has shown that in contrast to Shklovskiy's observations, this decay can be explained by the combined effects of the Martian Tide and the braking effects of the atmosphere residue at the altitude of PHOBOS. He called to our attention that the 11-year solar activity cycle may profoundly affect the Aerodynamic drag leading to a variable ratio of orbit decay. One could in turn conclude that orbital perturbations of PHOBOS would be a gage for the intensity of the solar activity at the distance of Mars and also measure the atmospheric density at PHOBOS' orbit. Mars orbiting satellites should be able to reflect and measure the same effects and report these back to earth. I bring this example to you only to show that we do have a constant influx of new knowledge, which in many cases will strengthen the scientific basis of our studies. However, every now and then a new bit of information is collected which appears to open up new questions.

Before I close, I would like to postulate that the real objective of our efforts is now to show that a C-5 type transportation system optimized for logistics support from earth can also work well if resupplied at the destination. This would be only an intermediate milestone of our efforts. The real effort should be to achieve a comparison between two systems -- one designed and optimized exclusively for resupply from earth and another one designed and optimized as a fully reusable system, making optimum use of Extraterrestrial Resources, being optimum safety-wise and as a next feature, being optimum cost-effectiveness wise. Based on my own preliminary studies, such a system will promise great utilizy in the further exploration of the solar system and will certainly extend the usefulness of chemically propelled transport vehicles beyond what generally is considered practical at this time.

I would like to further venture that the establishment of earth orbital terminals, a further development of manned orbital space stations, will eventually lead to the launching of fly-by probes from orbit rather than from the earth surface. It is quite obvious that this would reduce the number of operational steps after man laid his last hand on the equipment before departure and should so improve simplicity as well as reliability of unmanned as well as manned space probes. It is quite obvious that this mode of operation will demand an efficient earth surface to earth orbit transportation system. It is further quite obvious that the build-up of such operational modes will have to initially be based on use of Saturn C-5 and Titan III vehicles; these techniques will therefore live and operate side by side for a while.

In the hope that these thoughts have given you more exciting and stimulating food for thought, I wish the members of the Working Group and its organizational components a successful and rewarding annual meeting and more so, a successful year of work on a subject which rarely can be found more thought provoking. Thank you very much for your attention.

INFRARED EMITTANCE AND REFLECTANCE SPECTRA OF ROUGH AND POWDERED ROCK SURFACES

R. Lyons
Eugene A. Burns

This paper has been submitted to the Journal of Geophysical Research for publication and is not included in these proceedings.

DETERMINATION OF COMPOSITIONAL DIFFERENCES ON THE LUNAR SURFACE USING GROUND-BASED INFRARED SPECTROSCOPY

Graham R. Hunt
John W. Salisbury

ABSTRACT

The usefulness of molecular vibration spectra to determine the mineralogical composition of the moon by means of remote measurements has been demonstrated both theoretically and in the laboratory. Certain difficulties arise for ground-based observation, such as the disguising effect of atmospheric absorption upon the emission spectrum, changes in atmospheric absorption during or between spectral scans, grainsize variations, and temperature variations in the surface materials being studied. Despite these difficulties, it should be possible to unambiguously detect changes in the composition of surface materials from place to place on the moon. Such changes have been tentatively identified during preliminary experiments at Lowell Observatory during the winter and spring of 1964. Further measurement of the degree of heterogeneity of the lunar surface should provide information critical to the interpretation of the spot measurements of composition to be made by Surveyor and Apollo. It may even be possible, in time, to make a detailed map of lunar composition from the earth, using both ground-based and balloon-borne instrumentation.

INTRODUCTION

The purpose of this paper is to outline the techniques used, and present preliminary results obtained from the ground-based observational portion of a program currently being pursued at AFCRL, which is designed to determine the mineralogical composition of the lunar surface. Apart from the ground-based experiments, this program currently includes the use of a balloon-borne system containing a 24" telescope which is capable of operating at an altitude of over 100,000 feet, so that observations can be made from above most of the earth's absorbing atmosphere. The program also includes laboratory experimentation designed to provide a full understanding of the processes and techniques involved in the observations, and by means of which the empirical data are being collected which are necessary for the interpretation of the results obtained from direct observation of the lunar surface.

Because the primary concern is the determination of the mineralogical composition of the lunar surface materials, rather than elemental abundances, infrared spectroscopy is employed in all phases of the investigation. It is the most powerful diagnostic tool available for acquiring this sort of

information, because no two different materials exist which have identical infrared spectra, and because this technique is readily applicable for remote, nondestructive sampling.

GENERAL DISCUSSION OF THE TECHNIQUE

The characterizing information contained in the infrared spectra of solids results from transitions between the various vibrational energy levels which exist for the particular solid. For gases, additional data appear in the infrared spectra, due to transitions between the rotational energy levels, but in solids the ability to rotate does not exist.

It is important to appreciate that the characterizing information in an absorption, reflection and emission spectrum of the same sample is presented in a somewhat different form, and hence data obtained by two different techniques is not necessarily immediately comparable.

An absorption spectrum is a plot of k, the absorption coefficient, against the wavelength. A material is characterized by the number, and position, of these maxima in k. The possible number of such maxima is dependent only on the number of atoms in the molecule or crystal, although the geometry of a particular vibration may preclude it from appearing in the infrared spectrum - i.e., it is a "forbidden" vibration. The positions of the maxima are a function of the atomic masses, interatomic distances and geometry, and the potential constants or interatomic forces. Some further characterizing data are available from a spectrum through a consideration of the relative intensities of the bands, and from the bandshapes themselves.

A reflection spectrum is somewhat different in appearance, particularly in the positions of the maxima compared with their positions in the corresponding absorption spectrum, although the reflection data is transformable to absorption data (Hunt, 1964). This is because the reflection data also includes n, the refractive index, as well as k.

The real and imaginary parts of the complex dielectric constant, namely, $\epsilon' = n^2 - k^2$, and $\epsilon'' = 2nk$, can thus be obtained from the raw reflectance data by means of the use of some transformation, such as the Kramers-Kronig relationship. In this, the reflectivity amplitude is given by $re^{-i\theta(\nu)}$ where $r = R^{1/2}$ and R and $\theta(\nu)$ are respectively the reflectance and associated phase angle, the latter being obtainable from the relationship.

$$\theta(\nu) = \frac{2\nu}{\pi}\int_c^{\infty} \frac{\ln[r(\nu')]}{\nu^2 - \nu'^2}\, d\nu'$$

Such a transformation can be carried out, however, only if all of the fundamental vibrational and lattice data are available, which usually requires that the spectrum is recorded out to very long wavelengths.

In the case of an emission spectrum of an inorganic solid, the spectrum will normally appear as its reflection spectrum subtracted from the corresponding black or grey body curve. If, however, the black body emission is due predominantly to cavity effects on the surface, because of surface roughness or particle size and mode of packing, very little characterizing spectral data will be obtainable concerning the composition of the material. Except in this latter case, the emission spectrum yields data in the same form as that obtained from a reflection spectrum, so again, the shape of the curve and the positions of the maxima are different from an absorption spectrum of the same material. However, independently of the experimental technique used, molecular vibration spectra are completely diagnostic of the molecular composition of the material being observed.

THE TECHNIQUE AS USED FROM THE GROUND

In the light of the information presented above, it is clear that infrared spectroscopic techniques should make possible remote compositional mapping of the lunar surface through analyses of the emission spectra recorded from the hot illuminated surface. However, when such observations are carried out on an unknown body, such as the moon, from the surface of the earth, several difficulties arise:

1. Infrared absorption by the earth's atmosphere. The earth's atmosphere is not transparent in the infrared. On the contrary, it imposes varying degrees of absorption at different wavelengths (Adel, 1946). Regions of the spectrum in which there is little absorption by the atmosphere are usually referred to as atmospheric "windows". For probable lunar materials, almost all the diagnostic vibrational data lies to longer wavelengths that 8 microns, and is concentrated in two regions around 10 and 20 microns, as shown in Fig. 1. This shows reflection spectra of four assorted polished rock samples recorded on a Perkin Elmer Model 521 spectrophotometer. Fortuitously, the two regions richest in diagnostic data correspond roughly to two atmospheric windows which extend from about 8 to 14 microns and from 17 to 24 microns, as shown in Fig. 2. In this Figure, the atmospheric absorption is shown as the cross-hatched areas, superimposed upon which is an emission spectrum of a sand-sized sample of Brazilian quartz. Almost all the atmospheric absorption in the 17 to 24 micron region is due to water vapor, so penetration of this window requires observation from a location which is particularly dry.

If the precise extent of atmospheric absorption were known as a function of wavelength, then it would be possible to determine the exact outline of the emission spectrum attenuated, or disguised by, this absorption. Unfortunately, the precise extent of the atmospheric absorption cannot be measured at the same time that the lunar emission is being recorded, so it is difficult to determine the absolute emission spectrum and hence the gross composition. It is possible, however, assuming for the moment that atmospheric absorption remains constant, to compare the disguised emission spectra from different areas on the moon, and to detect differences in their emission spectra caused by differences in composition. The degree of heterogeniety of the lunar surface materials that can be

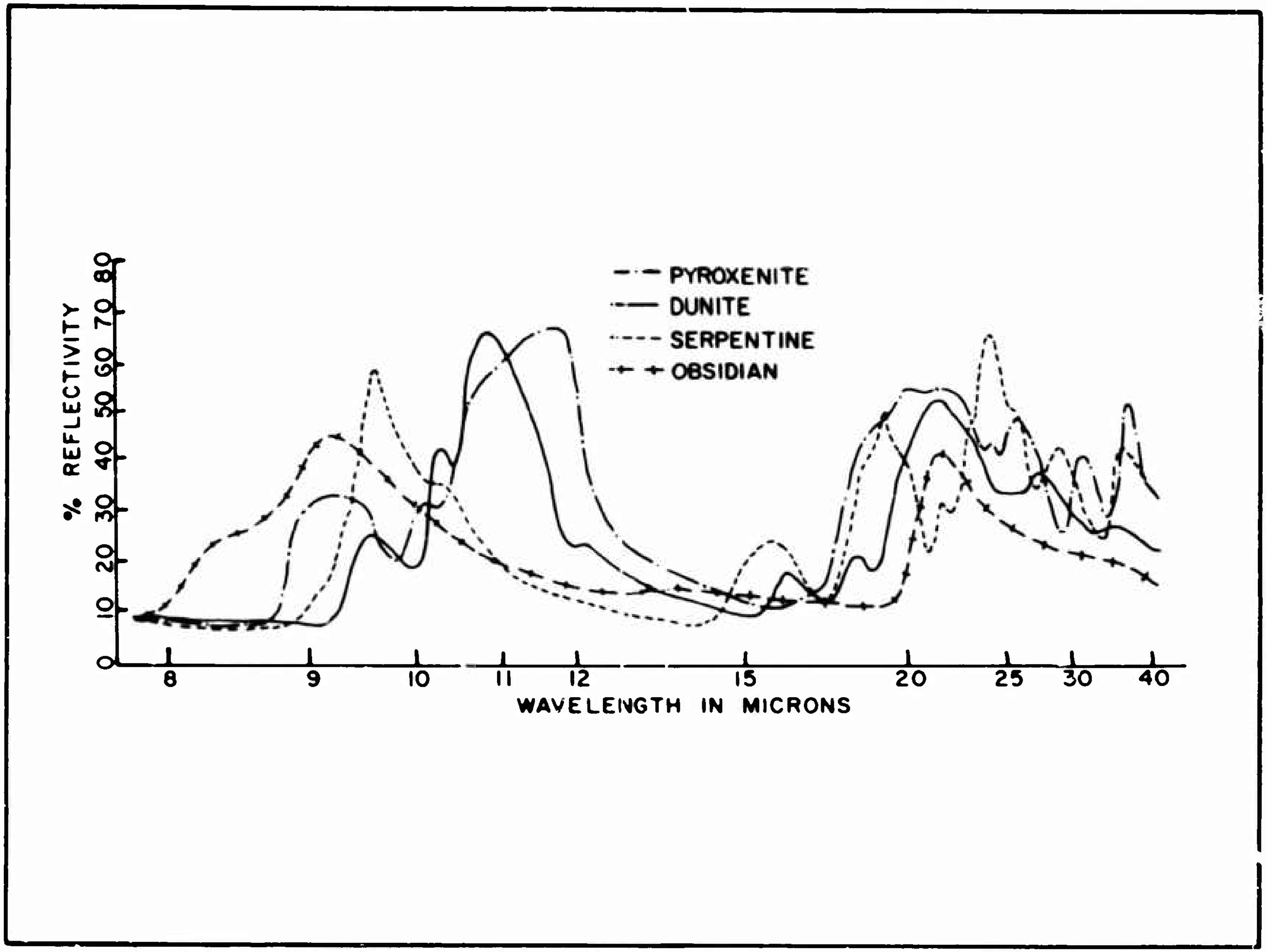

Figure 1 - Reflection spectra of polished rock samples recorded on a Perkin Elmer Model 521 spectrophotometer. Angle of incidence 13 degrees.

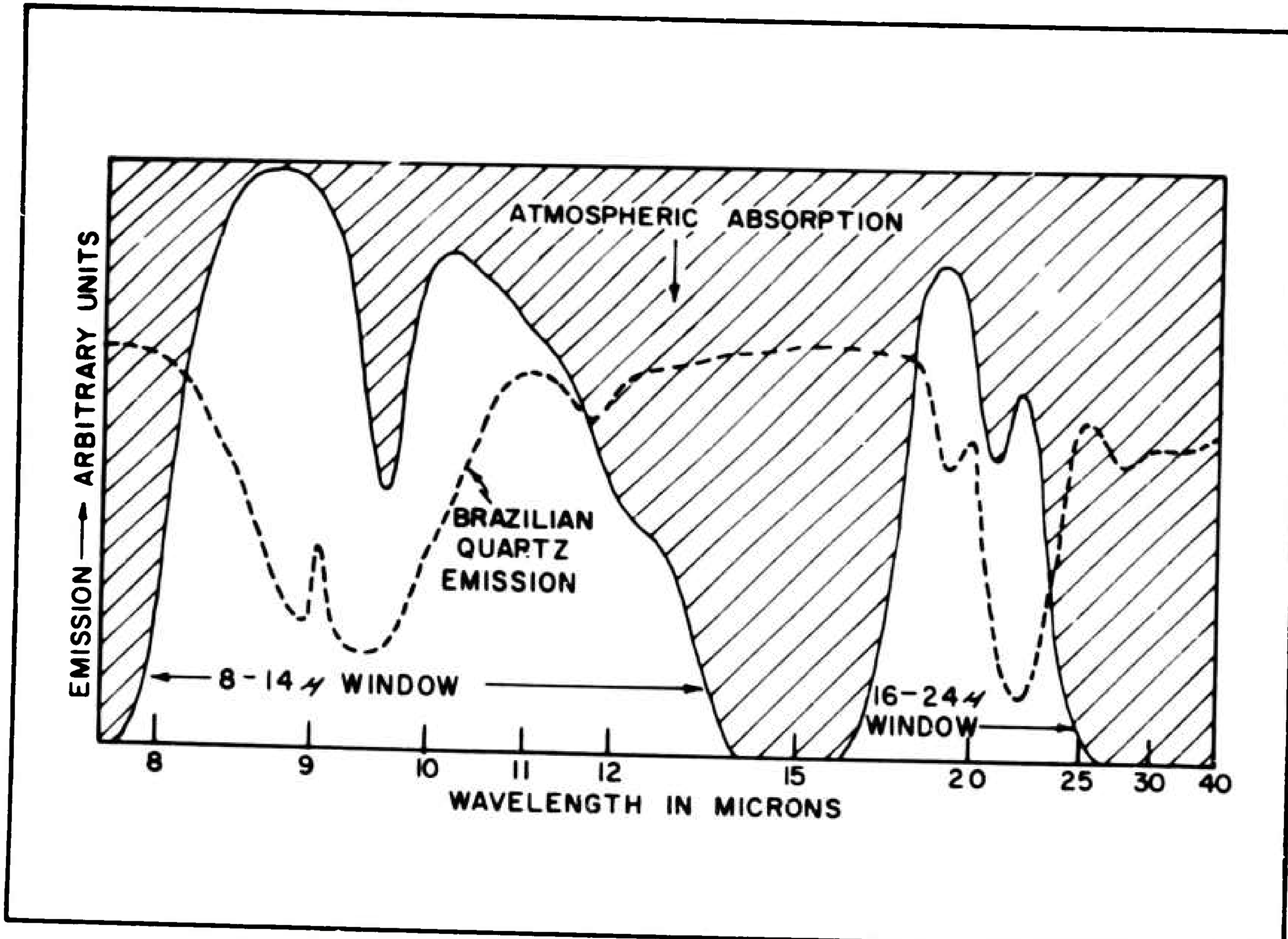

Figure 2 - Emission spectrum of coarse Brazillian quartz powder with atmospheric absorption spectrum superimposed. The relative amount of transmission through the 16-24 micron window is exaggerated.

revealed in this way is of extreme importance to an interpretation of both lunar history and the spot measurements of composition to be made by Surveyor and Apollo.

2. Changes in the earth's absorbing atmosphere. During the time required to sequentially record spectra from two different regions on the moon, any changes, particularly those in the water vapor content of the atmosphere, or due to nearly invisible clouds which front scatter could cause features in the difference plot of the disguised emission spectra which could easily lead to misinterpretation. It is extremely difficult to monitor such changes since, at the time when measurements are being made, no satisfactorily intense extended source (apart from the moon itself) is available as a reference. Spectra which were recorded a long time apart - or on different days - are therefore not directly comparable with confidence. However, if it is necessary to sequentially sample areas, such effects may be minimized by repeatedly recording spectra from two regions as rapidly as possible. This is not entirely satisfactory, since additionally the path length of absorbing atmosphere is continually changed during the observations, because of the change of position of the moon relative to the observation station. The only entirely satisfactory method of eliminating this complication is to record spectra from two areas simultaneously.

3. Temperature differences. Because the peaks of the Plank black body curves associated with lunar surface temperatures occur in one of the two spectral regions of interest, it has been suggested (Murray, 1964) that the resulting lack of parallelism of different temperature curves might produce spurious spectral differences. These effects are illustrated in Fig. 3. In Fig. 3a are shown spectra obtained from two regions between which the only difference is a temperature differential of 100°K. Subtracting one spectrum from the other yields a difference curve, which consists of a steeply sloped curve superimposed upon which is a spectral feature. This selected spectral feature is very pronounced in both the original spectra.

Figure 3b illustrates, by means of the most extreme example, the effect of a very large temperature differential within one sampled area upon the resulting integrated energy curve. In this sampled area we have selected the conditions which will produce two black body curves crossing at the smallest vertical angle possible. To produce these curves we assume an area composed of part of the sample being at 400°K, since this curve has its maximum at 7.3 microns, and the rest of the material is 200°K colder at 200°K. This latter curve has its maximum at 14.5 microns. To cause two such curves to cross, as shown, requires that the area be composed of 3% at 400°K, and 97% at 200°K. Even under such extreme conditions, the energy curve for such an area is surprisingly smooth, and appears as only part of a broadened black body curve with its maximum flattened and lying somewhere between the maxima of the two extremes. Material in the sample existing at any intermediate temperatures will only serve to sharpen the curve somewhat at the maximum, but no combination of black body curves will produce a sufficiently sharp feature in the energy spectrum for a region which could be mistaken for vibrational spectral data. In any event, to produce an area such as the one

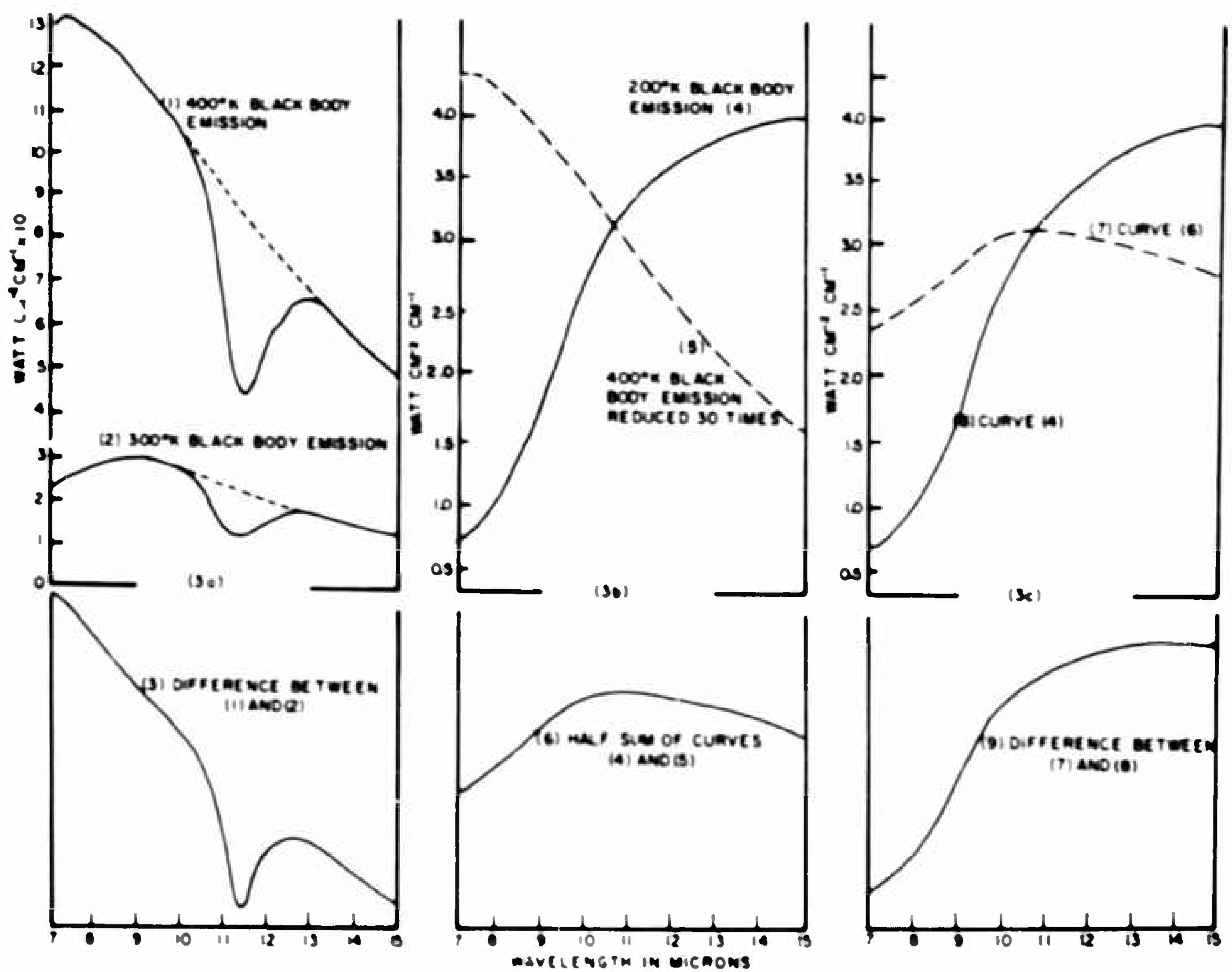

Figure 3 - Temperature effects on emission spectra. The characteristic difference plot between two uniformly heated samples at different temperatures is shown in 3a, and between a uniformly and non-uniformly heated sample in Fig. 3c. 3b illustrates the resultant energy curve for a sample non-uniformly heated containing a large, sharp temperature differential.

described above would require that the vast majority of the area be in complete shadow. Fortunately, any small effects from such an occurrence are virtually nil for observations made at or near full moon. It is, however, a factor to be considered in temperature determinations from radiometric measurements.

Figure 3c shows the difference curve between the energy curve from an area having more than one temperature, such as described above for Fig. 3b, and a black body curve at 200°K. Again, the curve is relatively smooth and sloping, demonstrating that the difference curve, like the integrated energy curve, shows no spurious spectral feature.

4. Differences in particle size or surface roughness. The only effect on the spectrum caused by roughening a sample surface, usually accomplished by grinding the sample to smaller particle size, is to reduce the spectral contrast (Van Tassel and Simon, 1964; Burns and Lyons, 1964). Such treatment in no way alters the positions of the maxima or minima which appear in the initial spectrum.

In Fig. 4a the emission spectrum of dunite is shown for two rough (fine-grained) a 1 one smooth sample (coarse-grained). The two rough samples differ only in their temperature. The difference curves obtained by subtracting the spectra of the two rough samples in turn from that of the smooth sample are shown. The difference curves (4 and 5) are identical except that they are displaced relative to the arbitrary reference difference curve. These difference curves also retain to a certain extent the spectral features of the original spectra, but it should be noted that the form of the curve is such that the feature all appears on one side of the reference line produced at the level where no spectral feature appears.

5. Genuine compositional differences. The difference curve which is characteristic of a genuine compositional difference existing between two samples from which the spectra were obtained is illustrated in Fig. 4b. The original samples used in this illustration were a serpentine and a dunite. The features in the difference curve appear both above and below the reference line, with a sharp crossover between them. In view of the above discussion, it is difficult to visualize any situation, apart from a rapid change in atmospheric conditions during the recording of the original spectra, which could produce such an effect other than a genuine compositional difference. The effect due to compositional differences is further illustrated in Fig. 5, which serves to illustrate how such compositional difference data is extracted from the information obtained by direct observation of the lunar surface.

In Fig. 5a, curve 1 is the 300°K black body energy curve. Curve 2 is the emitted energy curve for a sample of serpentine. Curve 3 is the energy curve which would be recorded when the atmosphere attenuates curve 1 - i. e., it is the atmospheric absorption spectrum using a 300°K black body source. Curve 4 is then the emission spectrum obtained using curve 2 as the energy source. This is then what the spectrum of a portion of the moon composed entirely of serpentine material would look l'k if observed and recorded from the ground. The emission spectrum a

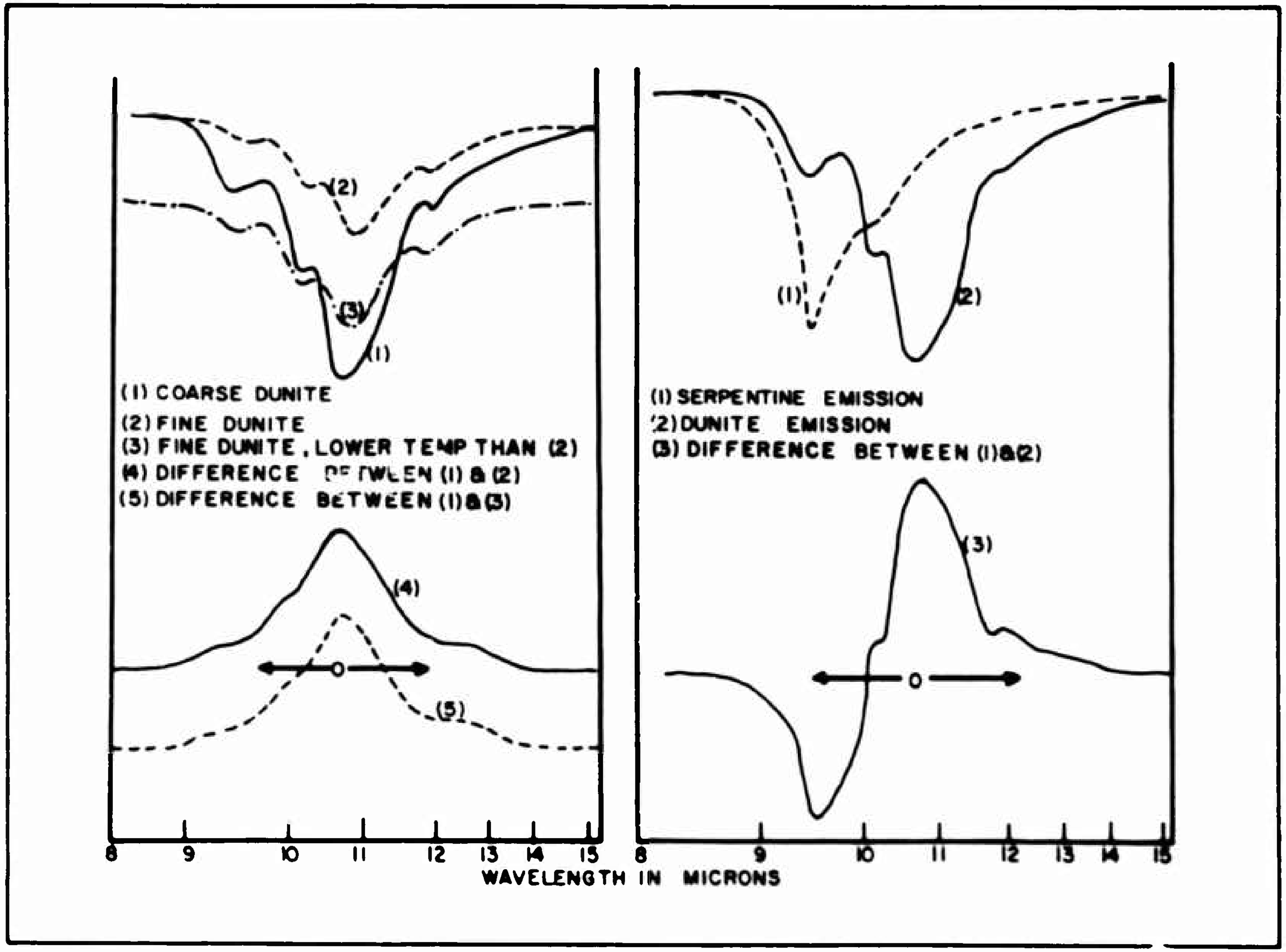

Figure 4 - Characteristic difference plots for samples which differ only in particle size (left) and for samples between which a compositional difference exists (right).

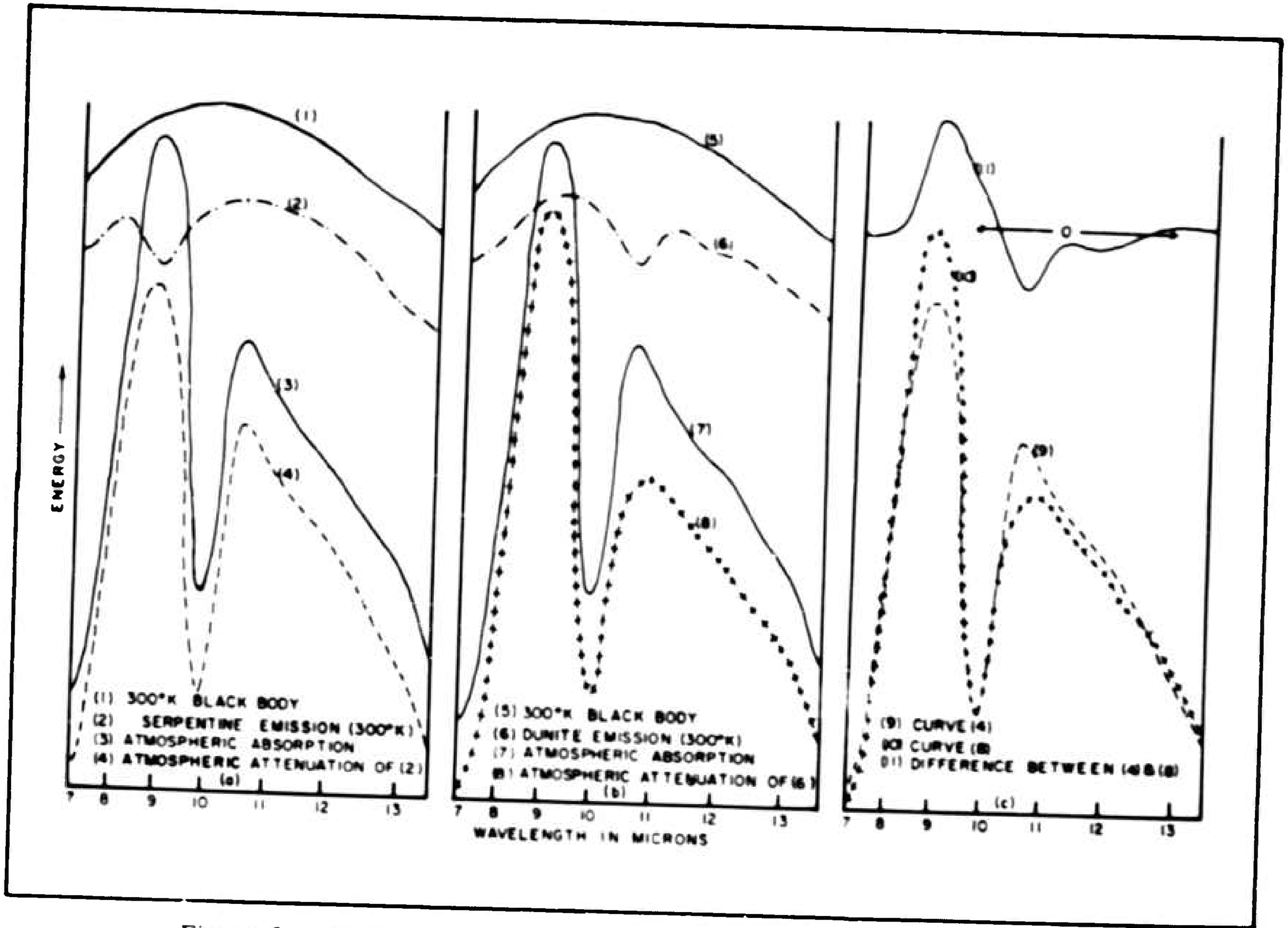

Figure 5 - Form of spectra which might be obtained from different regions on the lunar surface attenuated by atmospheric absorption. For explanation see text.

dunite sample at 300°K is presented in Fig. 5b in the same fashion as the serpentine emission was presented in Fig. 5a. In Fig. 5c, the dunite curve is subtracted from the serpentine curve to yield a difference plot curve (11), which is in the form of the difference plot shown in Fig. 4b, and so clearly indicates the compositional difference.

LUNAR OBSERVATIONS

Observational measurements of the infrared emission spectra from some features on the lunar surface were commenced at full moon in February 1964. Initially, we were interested in exploring the 16 to 24 micron region to discover if it was possible to significantly penetrate this partial atmospheric window (Hunt and Salisbury, 1964). It was thought that, because the majority of atmospheric absorption in this region is due to water vapor, if it were possible to penetrate the region at all, it would prove to be clearer than the 8-14 micron region, in which the 9.64 micron ozone absorption band remains intense throughout the year. Additionally, any effects due to temperature differentials within a sampled area would be minimized in this spectral range.

Accordingly, the instrumentation was specifically designed to operate in the longer wavelength region. The measurements were made using the 42" telescope at Lowell Observatory, Flagstaff, Arizona, because the high location of the Observatory (7400 ft.) in the arid Southwest offered the dryest observing conditions available.

The instrument used was a modified Perkin Elmer 98 spectrometer equipped with KBr optics and a Golay cell for detection.

Spectra in the 18-24 micron region were recorded from four lunar surface features. It was found that this region could be penetrated effectively even though the surface humidity was quite high (38% in the late evening to 33% in the early morning at 23°F and 19°F, respectively). The above described conditions existed on 26 February 1964, and this was the only time that weather conditions have permitted observations in this region so far. It is not expected that the window would be open during the summer months. The four lunar surface features selected to be spectrally scanned were the Central Highlands, Serenitatis, Copernicus and Tycho. The spectra were recorded by selecting two of the areas, and running spectra sequentially and repeatedly as close together in time as possible between these two. Then two others were selected. The time required to reach equivalent points in the spectra of different regions was about 4 minutes. The sample size on the lunar surface was approximately 80 X 480 km, with the long dimension of the slit being oriented approximately east-west. The spectra obtained are shown in Fig. 6. The curves shown are direct traces, without smoothing of continuously recorded spectra. The noise level was less than 1% and the resolution better than 0.4 microns. Between 17 and 21 microns the spectra were recorded with a gain setting of 1.5, while between 21 and 24 microns the gain setting was 2.5. The emission intensity from Tycho is much less than from the other 3 features due only to its lower temperature. Of most importance in Fig. 6 is the difference between the spectra obtained from Copernicus and

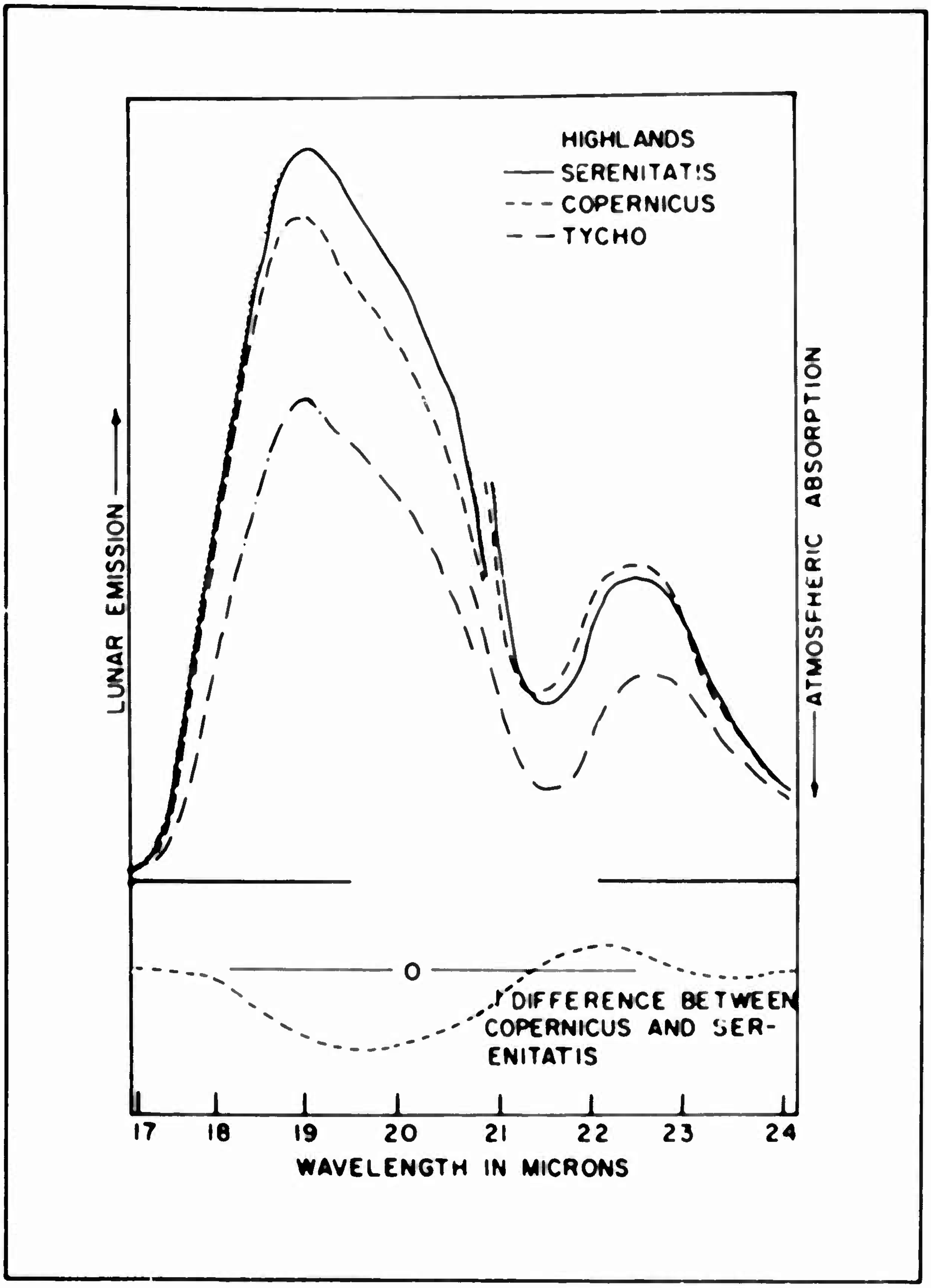

Figure 6 - Emission spectra of four lunar surface features as detected through the 16-24 micron window. Amplifier gain of 1.5 between 17 and 21 microns and 2.5 between 21 and 24 microns.

Serenitatis. The intensity of emission from Copernicus is less than from Serenitatis at 19 microns while it is greater at 22.5 microns. This type of behavior is typical, as outlined above, of a compositional difference.

Further observations were made at full moon in March and April 1964. Unfortunately, the high humidity and cloudy weather conditions precluded making observations in the 16-24 micron region, no observations were made in the 8-14 micron region.

Since our instrumentation was equipped essentially to perform at longer wavelengths, the resolution in the 8-14 micron range, using a KBr prism, was quite poor. At such resolution, the characteristic spectral features become broadened, and so cause much smaller changes in the emission intensity at a particular wavelength.

The major benefits derived from the measurements made in this region were indications of ways in which our instrumentation and recording procedure could be improved. The necessity to increase the resolving power of the instrument was immediately obvious. The uncertainty as to the characteristics of the atmospheric variations indicated the absolute necessity for simultaneously recording spectra from two different regions if this variable is to be removed. The possibility of internal compositional differences within a particular sampled area was pointed up. This further indicated the necessity for extremely accurate tracking of the selected area during the recording of a spectrum.

We examined several lunar features in this region and discovered what appear to be compositional differences between some of them. We do wish to emphasize the fact that these results require the confirmation of further observations. However, the most marked of the possible compositional differences was a difference between the spectra obtained from the Haemus Mountain area and Serenitatis. In all some 20 spectra were recorded from Haemus and 15 from Serenitatis. In the majority of such spectra a difference in intensity between two spectra were observed (as shown in Fig. 7). Although at no time was evidence collected which contradicted such a result, in several cases the difference was barely discernible. These latter results seemed to indicate that either internal differences could exist in Serenitatis, or that the forward scattering of a high thin haze layer in our atmosphere was eliminating spectral detail. From the relatively few spectra recorded from Kepler, the same sort of difference seems to exist between it and Serenitatis as was noted in the case of the Haemus Mountains.

Time has been acquired on the 69" telescope at Lowell Observatory for observations during full moon in December 1964 and January and February 1965 in order that further observations, designed to confirm the presence of compositional differences on the lunar surface, may be made.

Both the spectral regions, the 8-14 micron and 16-24 micron region will be explored using more sophisticated equipment. This instrumentation consists essentially of a double monochromator system which will allow a large degree of flexibility of operation. Briefly, the possible modes

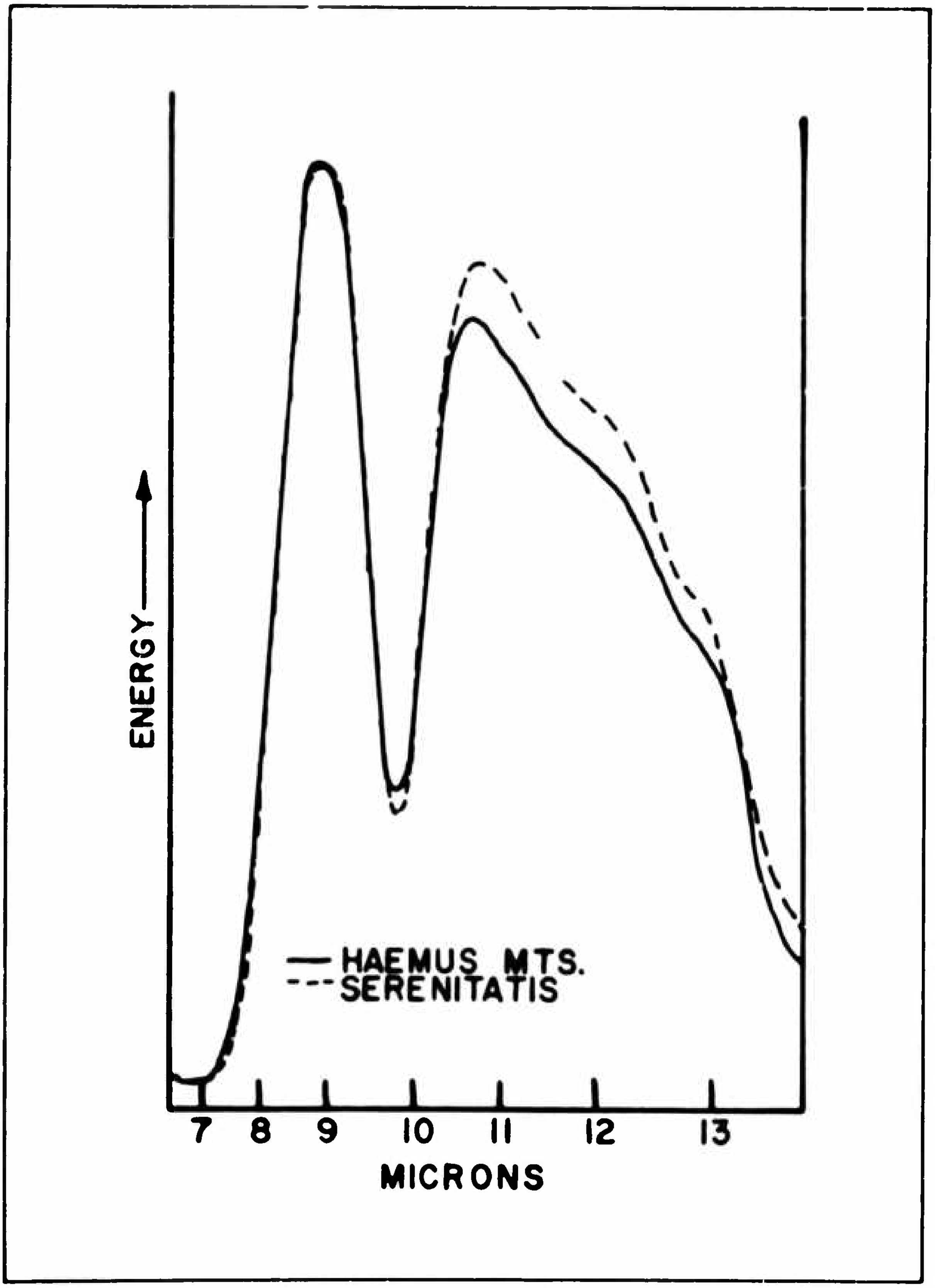

Figure 7 - Emission spectra of two lunar features through the 7-14 micron window.

of operation are:

a) Scanning the moon and recording simultaneously the difference at two selected wavelengths for a particular area. By selecting the wavelengths such that one corresponds to a minimum in an emission spectrum from a basic rock type, and the other to the minimum for an acidic rock type, areas of probable compositional differences will be located.

b) Sampling two different areas and chopping between them, direct difference curves can be recorded, which will eliminate any atmospheric effects as well as most detector and instrumental effects.

c) Using two detectors each recording direct emission spectra from the same area but staggered by any amount in time.

CONCLUSIONS

The usefulness of molecular vibration spectra to determine the mineralogical composition of the moon by means of remote measurements has been demonstrated both theoretically and in the laboratory. Certain difficulties arise for ground-based observation, such as the attenuating effect of atmospheric absorption upon the emission spectrum, changes in atmospheric absorption during or between spectral scans, grainsize variations, and temperature variations in the surface materials being studied. Despite these difficulties, it should be possible to unambiguously detect changes in the composition of surface materials from place to place on the moon. Such changes have been tentatively identified during preliminary experiments at Lowell Observatory during the winter and spring of 1964. Further measurement of the degree of heterogeneity of the lunar surface should provide information critical to the interpretation of the spot measurements of composition to be made by Surveyor and Apollo. It may even be possible, in time, to make a detailed map of lunar composition from the earth, using both ground-based and balloon-borne instrumentation.

ACKNOWLEDGEMENTS

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DISCUSSION

DR. STEINHOFF: Have you checked how much your atmospheric attenuation would be at about 40 thousand feet, flying in an airplane? There should be more than 80 percent of the total atmosphere below you, and this should considerably affect the infrared transmission of the atmosphere.

DR. SALISBURY: We haven't made studies at 40 thousand feet, because we have a balloon system the float altitude of which is 110 thousand feet. When we made studies at this altitude, we found that there is better than 95 percent transmission in most of the region of the spectrum, the only exception being at 9.6 microns due to ozone. There the transmission is only about 80 percent. With this sort of transmission, we hope that our balloon borne instruments will get true compositional data, not just differences.

DR. SINTON: What I am worried about is these atmospheric absorptions. If they were on a different scale, you might have a false difference.

DR. SALISBURY: You are saying the two areas are a different temperature?

DR. SINTON: Yes, and in two areas of different temperature, in the cases you illustrated, it was simple multiplication of the bands of serpentine and temperature curves. This is exactly the same multiplication I presume with the ozone band and black body radiation attenuated by it. If there isn't any emission band and you are looking at areas of different temperature, you could get into trouble with a straight subtraction. In addition, the 16-24 micron region is a lot more cut up with stronger bands than the resolution you have had to show.

DR. SALISBURY: We have three or four variables here, and it gets very complicated to think of them separately and still think of them together in all combinations. I think we have run through all the possibilities, though. With reference to different temperatures and no spectral feature, you do get a band from the ozone that would just be a negative feature. You wouldn't get a positive feature on the other side of it. Where we just get a negative feature, we ignore it.

I hope that answers your objection, and with regard to the fine structure in the 17 to 24 micron region, we did not want to resolve it. We don't need that kind of resolution to pick up the silicate band, I think we had .4 micron resolution, there, and this is the way we wanted it. But you are right, there is a lot of fine structure in there.

DR. LYON: I want to point out that the use of infrared spectroscopy to determine silicate composition is well described in Coblentz's work, 1910-1915, where he says we will never know the answer till we float our instrument in a balloon

BIO-ASTRONAUTICS ASPECTS OF SOVIET RESEARCH

Grady L. Mitcham

C. WILLIAM HENDERSON: Last September Grady L. Mitcham and I, were fortunate enough to be invited to Warsaw, Poland, to the XVth International Astronautical Conference. While there, we both participated on a panel for Lunar International Laboratory and we heard papers presented by the Soviets. As a consequence we also met a few Soviets in informal sessions. Because of this we are now experts on Soviet Lunar planning. As a consequence, we were invited to speak here on this subject, so we are going to present to you what we were able to discover by merely hearing a few papers. Mr. Mitcham will lead off by discussing the Bio-Astronautics aspects of it, from the point of view principally of long stay times as he sees the Soviets are developing a capability.

MR. MITCHAM: Good morning gentlemen, there is nothing better than being an expert on something that you really know very little about and I have to admit that I am an Aeronautical Engineer and am not an expert on Bio-Astronautics. I personally felt that the sessions there were quite informative as far as the material disseminated by the Russians, particularly in the area of orbital mechanics and flight trajectories and, also in the area of bio-astronautics and space medicine. There were seven papers on the latter subject given during the September 7-12, 1964 meeting. I won't attempt to read through all these papers, but what I have done, with the assistance of Dr. A. J. Pilgrim, head of Boeing's Bio-Astronautics Section, is to summarize some of these papers and, also point out a few of the highlights that might indicate in September some of the Soviet experiments that were suited for the most recent Voskhod flight. I would like to start off by a brief summary of a paper by I.T. Akulinichev and R.M. Bayevskiy entitled "Evaluating the State and Activity of Crew Members Under Conditions of Prolonged Space Flight". The methodology and instrumentation selected for interplanetary flights must be based on the data obtained in early experiments and the successful completion of earth orbital flights. The peculiarities and new problems of extended space flight will play an important role.

To ensure the well being of humans, reliable and active medical supervision (this is a very key point, they keep stressing in this paper that you need a medical trained man in the space craft and, this is what happened in their latest flight, the three-man space craft) as well as physiological and health investigations are essential to permit forecasts of their condition for the required period of time. The difficulty in providing biomedical support arises from the need to send along large supplies of terrestrial atmosphere, food, water, and devices to protect them from heat, cold, intense light, and cosmic radiation.

While human initial penetration of space has been accomplished on the basis of earth orbital flight, lunar and interplanetary flights will certainly require the preparation of an entire expedition, involving changes in the whole modus operandi of space research. Irregular work schedules do not appear applicable, but the organization of a "space service", where man will be able to stay in a space station for a longer time and perform tasks directly in space, appears necessary.

Space biology and medicine will play a distinct role. Automatic machines and bio-indicators, in addition to the testing of life support systems in earth orbital flight to collect biomedical information and reliability of the subsystems will be necessary.

Safety considerations within the space capsule should be controlled by doctors in flight and from the earth. Conditions and activity of the astronauts who leave the craft will be monitored with the help of instruments. Indicators on a panel under the scrutiny of an expert.

Since the astronauts will wear a space suit or "G suit" techniques will have to be devised for removal and replacement of the suit without impairing air-tightness or causing them discomfort. Once a problem of whether a man can actually exist for extended periods of time in space is answered it is necessary to determire man's capabilities, activities, and various duties. It was found in early space flights that functional changes were manifested in the form of impairment of fine coordination of movements in connection with such familiar conditioned acts as handwriting.

This is all I will discuss about this paper, but this is one of the papers we went through after the meeting and after the translation was performed it looked as if a few weeks prior to the Voskhod flight there were indications that the space craft would carry, probably, an astronaut, possibly a scientist, and in particular would have a man experienced in medicine, a doctor on the space flight.

Discussions with some of the key scientists in both formal and informal sessions indicated that the Russians feel very strongly about man's participation in space flight; in fact, there were excellent movies shown on weightlessness tests and also tests conducted with animals. One of these tests was a dog which was placed in a rocket, of the Redstone variety, which was launched and the dog was recovered with the instrumentation and various scientific measurements. In fact, the quality of the work looked to be very similar to what we have done in the U. S. on the test of short periods of weightlessness in various types of aircraft.

One of the key points that was made, was the fact that the Soviets have actually been conducting tests with men for up to 120 days in closed hermetically sealed chambers and, I might quote a few comments from this particular paper, entitled "General Principles Concerning the Reaction of the Organism to the Complex Environmental Factors Existing in Spacecraft Cabins" by A.V. Lebedinskiy, S.V. Levinskiy, and Yr. G. Nefedov.

"Under ordinary conditions the vital processes of the organism depend mainly on the influence of the environmental medium. In a hermetically sealed space, the medium is modified by vital processes of the organism. Chamber tests were carried out, lasting from 10 to 120 days. The effects of man on the chemical and microbiological properties of the medium were determined. The effects on man of such environmental factors as noise, small doses of ionizing radiation, and periodic rises in temperature were determined.

"An increase of airborne bacteria resulted from the increase of micro-organisms in the skin and was attributed to a drop in the antibacterial action of the skin.

"Metabolically produced carbon monoxide caused autointoxication shown by the appearance of carboxyhemoglobin in the blood and of definite changes in the central nervous system. The atmospheric concentration limit of substances excreted through the lungs should be kept low enough to permit their normal elimination from the body. For this reason, they recommend a maximum permissible concentration (MPC) of 3 to 5 mg/M^3 for CO and a CO_2 limit of 0.2 to 0.3 percent for confinement of more than 4 months.

"The effects of autoinfection have not been sufficiently studied.

"An analysis has been made of the changes taking place in the body during sealed chamber tests. The magnitude of these changes depends on the deviation of environmental conditions from normal.

"During the first phase, 10 to 15 days in 60-day tests, an initial physiological adaptation takes place. The circulatory rate decreases as does the work capacity. Reaction time and numbers of errors increase.

"As the man adapts to the new conditions, many functions stabilize. Sleep, motor reactions, light sensitivity of the eye, and number of errors drop to normal. Work capacity and fatigue threshold remain lowered.

"An "emergency reaction" takes place as subjects slowly readapt to normal, outside conditions. This took about 2 months after the 60-day tests.

"Additional air purification to remove bacteria and noxious chemical impurities, UV irradiation of the skin, increased vitamin intake, and special physical exercises plus a gradual transition of subjects from ordinary life conditions reduced the intensity and duration of the transition reactions.

"Increases in temperature, noise, and low level ionizing radiation did not cause any specific reactions in most cases but did cause generalized stress reactions: increases in nervous activity, blood flow, respiration, metabolism, etc. Ionizing radiation (0.3 rad, they say elsewhere) or 105 db noise will cause 40 percent increase in excretion of amino compounds, both together cause 80 percent rise.

"The specific hematological effects of ionizing radiation are reduced when other stresses are kept low, i.e., radiation tolerance is greatest when the environment is near normal, maintaining favorable "air livability" constitutes, one of the most pressing problems.

"Morale was good, on the whole, because of a feeling of responsibility and teamwork. The subjects understood their tasks and tests and did some useful work most of the time.

"Although there were individual variations between subjects, the adaptive changes were similar in all.

"Individual variations in such things as exhaled volatile compounds and microbiological flora suggest that the problem of compatibility of subjects on a broad biological plane merits

considera.ion along with psychic compatibility."

This particular paper did indicate that the Soviets are pursuing a rather aggressive program of long stay times whether they are applied to earth orbital missions or the possibility can be applied to extended stay times on the lunar surface.

In a paper entitled "Certain Problems and Principles of the Formation of a Habitable Environment Based on the Circulation of Substances" by A.M. Genin and Ye. Ya. Sheplev there was quite a bit of discussion on artificial ecological systems for prolonged manned space flights. The authors indicate the stores needed by man can be reduced to minimum amounts by cyclic regeneration. The closed system will take man's metabolic products and reconvert them to an acceptable form. For long term missions, a full ration of 300 calories per day is suggested and chemical synthesis cannot at present be considered tangible and tissue culture methods require exotic media. They also state that biological systems seem to be required. From the nutrition standpoint they assign a normal of 10- percent animal food in man's diet and conclude that single celled algae may be less advantageous than certain higher plants. And, also they suggest that the use of poultry for example, may be more acceptable as an animal link in the food cycle.

I don't think this type of an approach is very different from our Biomedical programs within various government organizations and industry in the U.S.

However, it does point up to the fact that the Soviets are working on many of the same problems that we are and maybe to a greater extent in some areas. They presented experimental results of quite a bit of work done on the psychological reaction of the human organisms to transverse accelerations and the raising of the resistance to such forces. I do have copies of all these papers and, if any of you are particularly interested in some of these fields, you might contact me after the meeting and I can make arrangements to have copies mailed to you. I would like to repeat again my earlier remark that my impression and also the impression of participants who were Biomedical experts that the Soviets are pursuing a very aggressive experimental program with the use of man for long space stay times. They were not very explicit about what their space plans are as to whether they are plannning earth orbiting missions or lunar missions or lunar bases. However, I feel that the material that was presented did represent experimental data and, various experts I have talked to feel the same way.

DISCUSSION

MR. SPEGLER, Aerospace Research: I am curious if the Russians have retested the same subject to see if there is any long term learning or adaptation.

ANSWER: Yes, there was indication that they had retested the same subject in which the stay time varied from 10 to 120 days after various time periods and recorded body reactions.

MR. SPEGLER: I was curious if the individual had a long term adaptive capability where he would recover more quickly after each succeeding test.

ANSWER: I cannot answer that, I don't really know.

DR. EDSON: Did the records discuss tests in which there was adaptation to higher than earth gravity as to centrifuge, and did you find any evidence of their use of a lunar gravity simulator, such as we have at Langley?

ANSWER: I do not recall any presentations of a lunar gravity simulator of the type used at Langley. Some of the Langley movies were shown at the conference, however the Soviets did seem to concern themselves to a great extent with combined stresses which include combinations of G and radiation levels. Many Biomedicai experts feel this type testing is very important for long term boosted flights.

DR. EDSON: That's higher than one G plus radiation?

ANSWER: That is correct, their G levels, in fact to be specific, I'll take a look through this one paper. For instance they were testing vision at an 80 degree tilt angle and they went to a G profile of from 4 G's to 14 G's and this covers quite a spectrum, probably much higher than one would expect to get in most any boost system, so they are working at G's in excess of one G.

QUESTION: With respect to the loss of efficiency, is this strictly psychological due to confinement?

ANSWER: I think the loss of efficiency was from confinement and, also from the amount of radiation that was given the subject, they were testing other factors other than confinement, and have made a point that radiation levels that might be experienced in certain of our space craft may be much higher than one would like to have and there is evidence that they are doing a great amount of testing in which they are subjecting the man to close confinement and various levels of radiation and I got the feeling that there was a combination of the two, this loss of efficiency.

MR. MALCOM: Did they actually indicate what radiation levels they used for operations?

ANSWER: Yes, the radiation levels are indicated in the papers - I do not recall the exact numbers.

QUESTION: Did they list the radiation losses that they gave on these?

ANSWER: Yes, they did, I don't have these at my fingertips, however they are included in the paper and the period of time they gave them and they showed this quite openly in the papers.

CONSTRUCTION ON THE MOON

DO THE SOVIETS HAVE A PLAN?

C. William Henderson

The Soviets have usually been tight lipped about announcing their future space plans. Often hints of their programs have appeared in print or verbally, but usually couched in terms too vague to be recognizable. Last May at the COSPAR meeting, V. V. Parin, Vice President of the Soviet Academy of Medical Sciences is quoted as having privately remarked that the Vostok one man spacecraft had outlived its usefulness. He also mentioned the desirability in future flights of having a space surgeon aboard rather than rely on telemetry for physiological data. Needless to say, these words were a sneak preview to the next Soviet manned space exploit, the three-man spaceship, Voskhod.

What other hints have been given concerning the USSR space program? Though some people have always felt that the Soviets had a manned lunar landing goal in their plans, the recent achievements of the three man spaceship, Voskhod, have renewed speculation that the USSR is really in the moon race. Recent comments by Soviets associated with the Voskhod program would indicate that the race is definitely on.

A direct implication of Soviet lunar plans came from the recent remarks of Soviet airplane Designer General Artem I. Mikoyan (brother of Anastas) who said, "whatever secrets surround the earth's nearest neighbor, they will be solved by man. And one would like to believe that the first man on the moon will be our Soviet cosmonaut. We are confident of this. Confirmation of this may be seen in the flight of the space ship 'Voskhod' ".

Colonel Vladimir Komorov, the commander of Voskhod implied in a negative way that a lunar shot was possible by stating that his spacecraft, <u>in its present modification,</u> is not capable of going to the moon. He also was quoted as saying "Despite the advance in technology, <u>in its present state,</u> the Voskhod landing system cannot be used for a lunar landing". (He was referring to the retrorocket system for a soft Earth landing.)

It is interesting to note, however, the advantages of a retrorocket system for an earth landing. The experience with this system could lead to the development of a lunar landing capability while practicing Earth landings.

Also this type of system could be used for high velocity lunar trajectory approaches to Earth, slowing the spacecraft prior to earth entry. Though heavier because of its retropropulsion system, this method would greatly simplify the re-entry heating problem. While the United States is developing a re-entry heating system to off-set the high velocities of return from lunar distances, a retrorocket system may be the Soviet solution to this same problem despite the obvious weight penalty.

The Soviets, over the years have written some articles and have presented a limited number of papers about lunar exploration and lunar surface facilities. Their published efforts have been far less numerous than those in our country, and are extremely vague with respect to lunar surface installations, often time only mentioning the desirability of lunar bases.

It should be noted, however, that every engineer and scientist in the Soviet Union is a state employee, and consequently, cannot devote much effort to lunar base consideration unless specifically directed to do so by the government. This would imply that any lunar surface equipment studies are government sponsored, indicated official endorsement of the concept of lunar bases.

In 1962 the magazine "Soviet Union" referred to an article by the Chief Designer of Soviet spaceships (this man's name has never been identified in a publication), stating his concept of a space program as follows:

"The conquest of near-Earth space is a matter of the not too distant future. Manned flights to the Moon and trips to neighbouring planets," the article continues, "are quite feasible in the coming few years. First, presumably, automatic probes will be delivered to the Moon's surface. They will be followed by manned ones. The establishment of a permanent research station on the Moon, and later of an industrial project, will make it possible to exploit the as yet unknown resources of the Earth's natural satellite. Then will come flights to the nearest planets of the solar system, Mars and Venus."

In September of this year, the Soviet news agency TASS published an article entitled "Objective of the Soviet Space Program - the Moon". In summary the article said:

On the eve of the fifth anniversary of the launching of the first Soviet space rocket to the moon, correspondents asked (cosmonauts) G. Titov and A. Nikolayev about their future plans. Titov replied, "To visit the moon, and to live on it." Nikolayev said, "The moon--that is the scientific objective."

TASS continues, "everything now being done in space, including the launching of Polyot and Elektron vehicles has a direct bearing on travel to the moon. Very likely the first step will be an enormous earth-orbiting satellite carrying some 15-20 men to serve as a space port. Or else, "the author says, "heavy satellite will be launched around the earth first and the manned spaceship then launched from it towards the moon. Academician N. Semenov suggests that the moon may serve as a gigantic electric power station, converting solar radiative energy into electrical. The moon, in this scientist's opinion, is the most suitable place to build nuclear and thermonuclear stations. Academician V. Ambartsumyan, Soviet astrophysicist, proposes that telescopes be set up on the moon for astronomical studies. The Chief Designer of Spaceships is reported to have often said that the moon can become an excellent launching place for manned flights to Venus, Mars, etc., since its smaller gravitational pull will make possible greater carrier-rocket efficiency."

B. Lyapunov, the Willy Ley of the USSR, in discussing lunar stations indicated how they might be built and for what reason. He said that currently a great deal of importance

is being placed on lunar stations. The astronomer N. P. Barabashov, a member of the Ukrainian Academy of Sciences, writes: "In the future, as rocket construction improves, power capabilities increase, and space flights develop, it would be very interesting to establish a permanent space station on the Moon." The absence of atmosphere, the low gravity (one-sixth that of the Earth), and the possibility of equipping an underground dwelling which will assure protection against radiation and meteors makes the Moon very suitable for the establishment of a scientific space center for astronomical and other research. The center would serve as a base for interplanetary flights, as a powerful "heliostation" (if part of its surface were covered with semiconductor screens), and as a relay for radio and television broadcasts. Engineers planning such a station would also have to develop a lunar cross-country vehicle. Such a settlement would make possible a detailed survey of lunar conditions and, in time, lead to colonization of the moon. The problems connected with establishing stations beyond Earth are now being considered in the field of astronautics.

Possible lunar construction and utilization of lunar resources was indicated in August 1964 by A. Yushka, Chairman of the Vilnius Planetarium Council when he discussed survival on the Moon. In summary he said - "The first task of astronauts after landing on the moon will be to dig tunnels into the lunar surface to serve as living quarters. The tunnels would be hermetically sealed from all external influences. At first supplies would have to be sent from the earth. Later, however, air and water will be extracted from the lunar crust by means of sperical mirrors able to generate temperatures of the order of 3,000° C. The estimates of the American astronomer F. Zwicky are cited in this regard. Carbon dioxide, also extracted from the lunar rock, could at still higher temperatures be decomposed into carbon and oxygen. Ionized gases and electric current could be produced in the same way, thus providing a power base for some industry. Hydroponics offers the best means of food supply. The cultivation of algae, especially, seems most promising as a food source and as a means of purifying the air."

In September 1964 at the meeting of the International Astronautical Congress, a paper entitled "Architectural Problems in Lunar Construction" was presented by Soviet Architect I.F. Florov. This was the first paper on manned lunar stations ever presented by Soviet representatives at an international conference.

The paper was very general in nature, emphasizing the many hazardous conditions associated with the moon and suggesting the technological areas requiring further study. The basic emphasis was on the lunar station structure itself. As envisioned by the authors, a desirable lunar station structure would be a pneumatic shell supported by a rigid skeleton. The respiratory and pressurizing gas medium within the shelter would then become an actual structural component of the station. The inflatable material was not specified, but was mentioned as being elastic. The structure could be shielded from the lunar environment (meteoroids, radiation and thermal flux) by burying it below the lunar surface in a natural or man-made cavity.

To demonstrate the concept, the authors suggested one design which provides for a three story structure, each level approximating an inflated torus. These in turn are connected to a rigid central cylindrical shaft running through each torus and terminating in an

exit lock at the lunar surface. The cavity in which the shelter is located is backfilled with lunar soil so that the entire complex is buried below the surface. There is no mention of how the station is delivered to the moon or how it is emplaced.

This Soviet design of a lunar station differs markedly from recent United States Concepts. We, here, have considered both buried and above ground structures, but have rejected the former as an exceptionally difficult task to perform during the early phases of lunar occupation since it would require considerable blasting and soil moving capability. Also we prefer (at least at present) to have a completely rigid structure which does not rely upon pressurization for stability. This is desirable to insure structural integrity in the event of puncture and also to minimize displacement or disconnection of equipment and plumbing attached to the structure bulkheads.

The Soviet structure has three levels to take advantage of the cavity in which it is emplaced. The United States concept, being on the surface, is modular. This will provide compartmentation horizontally rather than vertically. We feel that this latter method is a more desirable characteristic, since it will permit unlimited expansion in several directions.

One unusual feature mentioned in the Soviet paper is the means of egress which is referred to only once, and very briefly at that. The quotation is "The upper end of the shaft will contain exits and hydraulic locks (air-liquid-vacuum) which will give a minimum loss of air."

Whether this statement refers to a lock which has its air expelled by flooding, then by pumping out the fluid to form a vacuum, or consists of a U-tube trap with liquid separating the atmosphere from the vacuum cannot be determined. In either event, men would have to be emersed in the fluid, and there would certainly be a liquid boil off.

There are considerable generalizations in this paper, many of which seem, on the surface, to be unstudied. It is difficult to assess whether this Soviet concept is merely a first serious look at lunar construction, or whether, by its being published, implies that it is now releasable, and that the USSR has far more intensive study efforts still under the cloak of secrecy.

EARLY MISSION EXPERIMENTS AND LUNAR RESOURCES EXPLORATION

Jack R. Van Lopik, Richard A. Geyer and Christopher Crowe

There is general belief that a program of scientific and exploratory work on the moon is a logical extension of, and is implicit in, the present national commitment to manned lunar landing. If this is indeed true, a maximum of scientific data should be obtained by each manned mission to assure effective design of subsequent lunar surface operations. For general planning purposes, this implies that:

a. Maximum use should be made of automatic devices to supplement the capabilities of a relatively small number of men with moderate life support requirements. Primary functions of the astronauts would be to act as scientific observers, make decisions concerning conduct of surveys, insure that scientific instrumentation is properly erected, and/or operate and maintain automatic data gathering devices.

b. As many instruments as possible should be designed for multipurpose use if this can be accomplished without materially reducing the effectiveness of any one measurement or experiment.

c. Scientific competence of the astronauts should be of the highest possible level.

d. Serious consideration should be given the use of the lunar environment or materials to permit reduction of operational and life support payloads and increases in scientific payloads.

Exploitation of lunar resources is the item that will require the most intensive scientific investigation.

Exploration Programs

The first goal of any program aimed at the exploitation of lunar resources is to locate deposits of suitable materials. Effective design of mineral or resources surveys is dependent, however, upon an understanding of lunar geology and structural, composition and/or physical property differences or contrasts between usable materials and the host or country rock. Ideally, much of the required data would be obtained with remote electromagnetic sensing systems--utilizing earth-based, earth-orbiting, lunar-orbiting, and lunar-impacting spacecraft. Unfortunately, as postulated terrestrial-lunar analogs of features cannot be accepted unequivocally,

valid interpretation of remote sensor data also depends upon at least an elementary knowledge of actual lunar surface and near-surface conditions. To provide crucial information concerning lunar surface properties, contact or on-surface measurements must be made prior to either (1) final selection of the most suitable or diagnostic noncontact techniques or (2) final interpretation of remote sensor data.

In spite of these difficulties, the overall plan for lunar exploration will undoubtedly follow the general pattern of conventional terrestrial mineral exploration. This pattern involves preliminary interpretation of aerial survey data to identify broad regions of interest and to outline gross features within these regions. Next, a ground survey is conducted within selected regions to delineate areas warranting more intensive investigation. Subsequently, surface and subsurface geological and geophysical studies are made of relatively small areas to assist in determining the presence or absence of mineral deposits. Any lunar exploration program will require hard- and soft-landing devices, launched either from earth or a lunar-orbiting satellite, to obtain information concerning lunar surface and near-surface conditions. Orbital reconnaissance satellites will be required to obtain extensive remote-sensor imagery coverage for use in accurately locating devices previously landed and in extending the point-source information obtained with these devices. On-surface exploration will be conducted through utilization of unmanned and manned roving vehicles and rocket platforms. A diagram of a possible lunar exploration sequence is included as Figure 1.

The type of data obtained by each manned or unmanned mission is dictated by the goals or objectives of the overall program. The Ranger and Surveyor programs, for example, have been oriented toward acquiring data to permit site verification for Apollo landings. If the overall goal was to establish a base on the moon, the sequence in which certain data are obtained and, possibly, the nature of the data might be different. There are, of course, data requirements common to both goals, and the present program will supply information that will aid in the planning of lunar resources surveys. However, the first opportunity to obtain information directly applicable to lunar resources exploration will probably be in connection with on-surface measurements made during Apollo missions.

Apollo Lunar Surface Experiments

Measurements or experiments to be made on the lunar surface during Apollo missions can be evaluated and grouped on the basis of their contribution to five fundamental lunar problem areas:

Identification and measurement of properties or phenomena hazardous to the astronaut

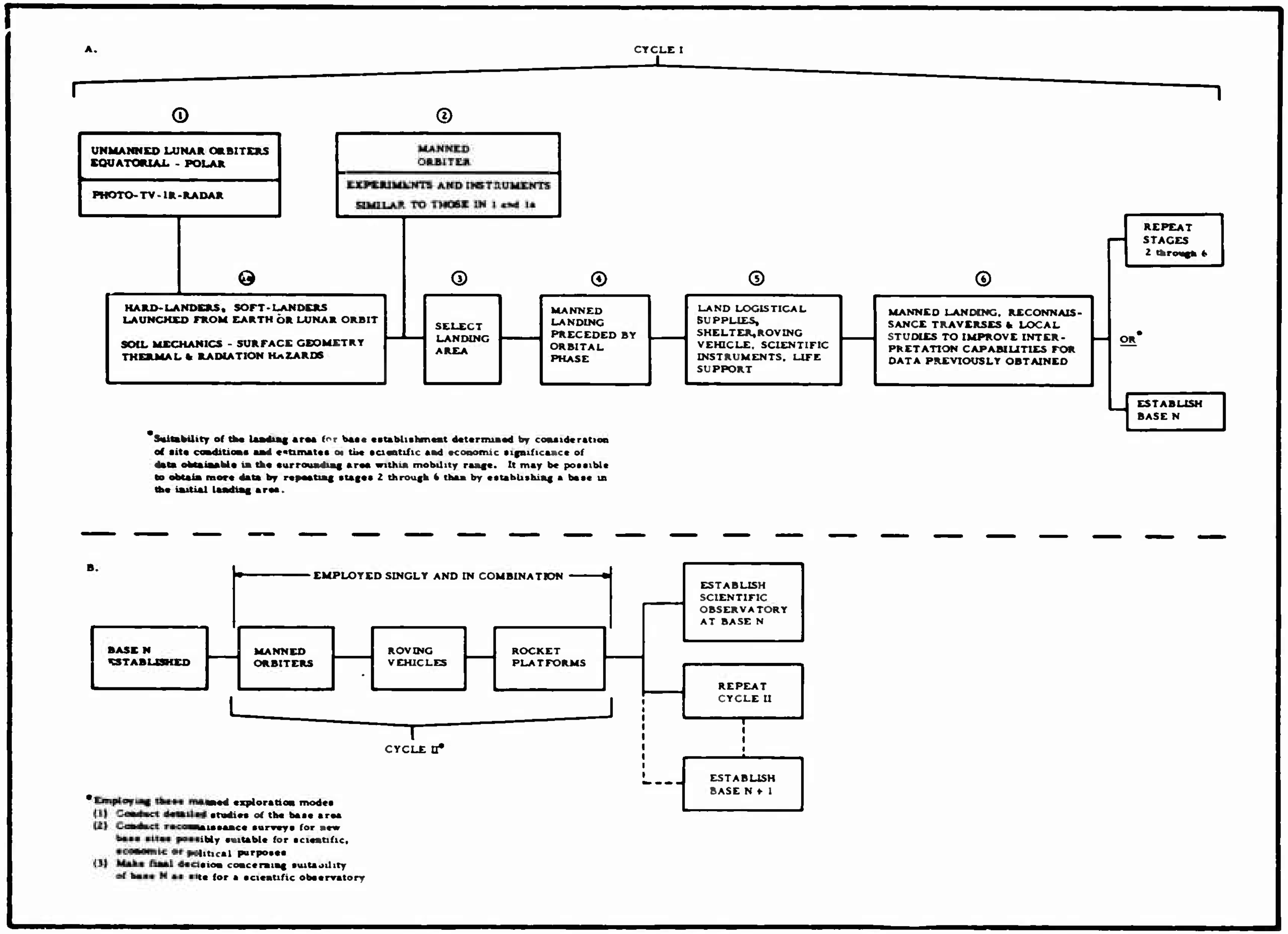

Figure 1. Possible Lunar Exploration Sequences

Determination of trafficability or suitability of areas for future landing sites

Solution of problems associated with lunar basing or resources exploration

Determination of the origin, nature and age of lunar surface features

Determination of the structure, origin and history of the moon and earth-moon system.

The groups are not mutually exclusive and measurements pertaining to each will be made on all missions. However, maximum emphasis during the first landing must be placed on those measurements related to astronaut safety and mission success--and associated measurements of scientific significance. On subsequent landings, environmental hazards are still of interest, but emphasis can be shifted toward lunar basing and more purely scientific tasks.

Numerous measurements/observations/experiments representing a wide variety of scientific and technologic disciplines must be considered. As schematically depicted in Figure 2, this requires a progression from numerous measurements or experiments to a few by means of successive evaluation or filtering. All possible experiments must be compiled and subsequently evaluated from the standpoint of (a) contribution to fundamental lunar scientific or technologic problem areas, (b) solution of specific lunar problems or combinations of problems, (c) engineering feasibility of conduct on the lunar surface, and (d) mission needs or constraints.

The total time devoted exclusively to scientific tasks during the first several Apollo landings will probably range from 4 1/2 to 9 1/2 hours. Astronauts will probably not be able to venture more than 1000 feet from the LEM, and only one will be outside the LEM at a time. The scientific payload is limited to 250 lb. Eight to fifteen cubic feet for storage of 170-210 lb of scientific equipment will be available within the LEM descent stage and subject to hard vacuum, extreme temperature, radiation, shock, and other launch, landing and environmental conditions. A two or three cubic feet storage compartment for 40-80 lb of equipment will be positioned within the LEM ascent stage and is protected from environmental hazards. A maximum of 80 lb of samples, film or recorded data can be returned to earth. Based on these constraints and the other factors implicit in the rationale described in the preceding paragraph, preliminary recommendations have been prepared concerning the composition of the scientific

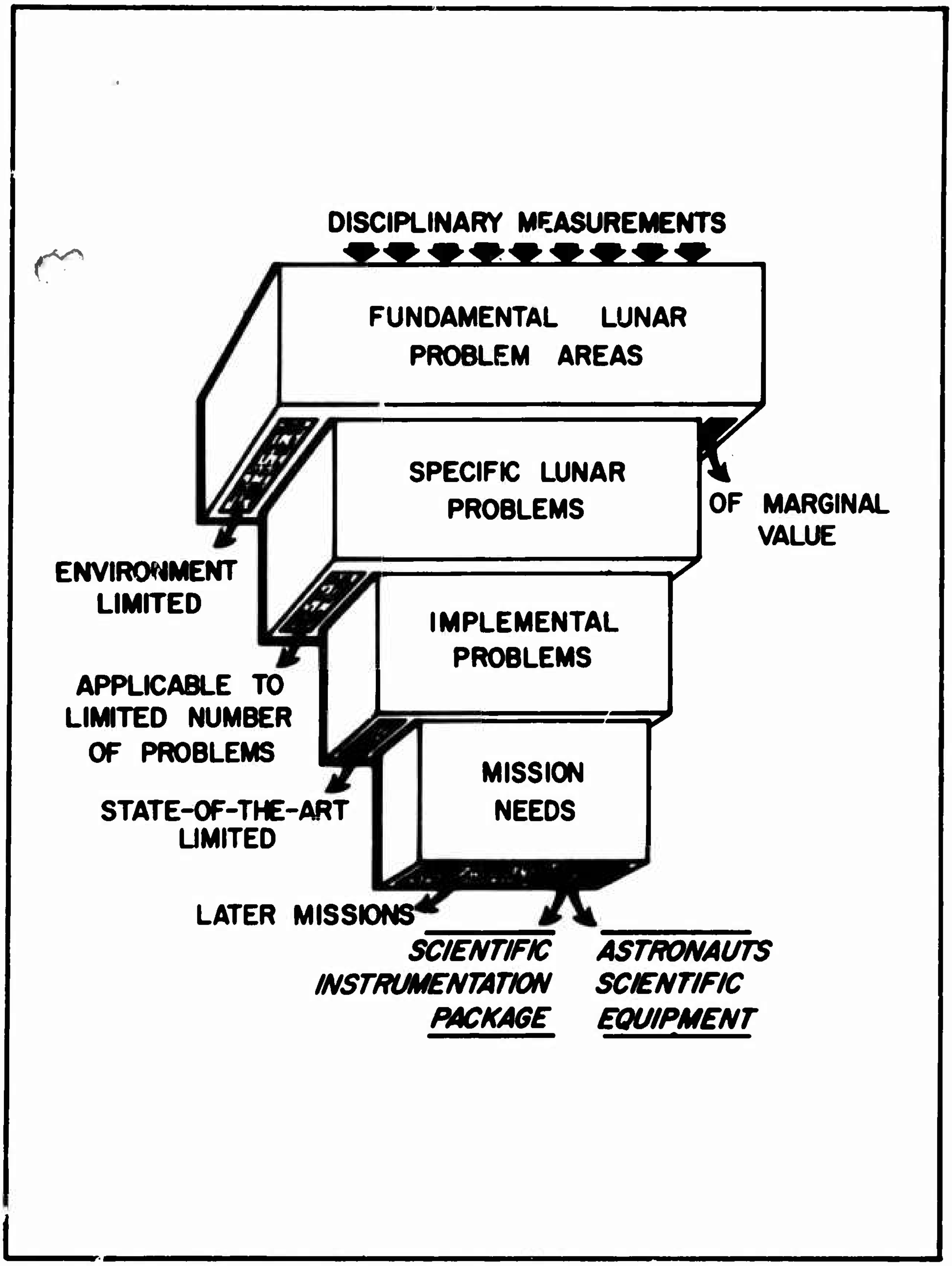

Figure 2. Experiment Selection Rationale

instrumentation payload for the first several Apollo landings. Recommendations for the first two flights are described briefly to illustrate the types of information that may possibly be obtained.

First Flight

The first landing will probably consist of two lunar surface excursions devoted to scientific data collection. The first excursion will be of 120 minute duration and the second, 150 minutes. The program is outlined in Table 1 which presents experiments in the order in which they are to be performed and an estimate of the cummulative time requirement for each.

Hazards - Measurement of hazardous phenomena or conditions has high priority on both the first and second landings. The primary hazard is believed to be radiation. This will be monitored by personal dosimeters and survey rate meters. One of the rate meters will be located in the LEM, and another will be left on the moon to monitor and transmit radiation data. Micrometeoroid infall and secondary ejecta may constitute a hazard to the astronauts, but the flux can be estimated by visual observation of surface impacts and the sounds generated by impacts on the LEM. These observations will not permit an estimate of the momenta and mass involved, and development of a specially designed micrometeoroid and ejecta flux sensor is highly desirable. However, the results of preliminary studies indicate that, for the first flight, the instrument weight is probably excessive for the value of the data obtained. Hazards presented by fine-grained surficial material, either because of great thicknesses or adverse electrical behavior, will be tested by observation of penetration of the LEM landing pads and by the astronaut during egress. Samples will be collected immediately to test for chemical reactivity and possible biologic content. Temperature recording devices in the LEM landing gear and in the astronaut's boots will warn against unexpected thermal hazards.

Next in importance is probably the mechanical condition of the surface. It is thought that really valid data concerning this hazard will not be obtained until the surface is tested manually with a staff or pentrometer. The fundamental decision as to whether the surface away from the LEM is safe for astronaut traverse depends on such surface characteristics as areal homogeniety, bearing strength, adhesion or bonding of surficial particles, roughness, and the presence of voids and crevasses. This decision must be made by the astronaut after noting LEM landing gear penetration and staff penetrometer measurements made during and after egress. Data obtained at one spot or in one locality may not be truly representative of lunar surface trafficability.

TABLE 1

WEIGHT, VOLUME AND TIME REQUIREMENTS FOR MEASUREMENTS, OBSERVATIONS AND EXPERIMENTS PROPOSED FOR EXCURSIONS 1 AND 2 OF THE FIRST FLIGHT

EXCURSION 1	Lb	In.^{3}	Min
Descent camera	6.0	230	
Descent camera printer (pre-egress)	3.0	320	
Personal dosimeters (2)	0.6	2	
LEM survey rate meter	1.0	70	5
Landing gear thermometer	0.5	4	2
Chemical reactivity detector	0.5	17	10
Boot thermometer	0.5	4	2
Camera and flash	5.3	90	
extra film and flash attachment battery	1.8	24	
Staff penetrometer	2.5	20	4
Tracking transducer	4.5	150	
Scientific Instrument Package (SIP)	152.7	11,286	20
Survey rate meter			
Transponder			
Combination seismometer			
Helium magnetometer			
Surface temperature loop (1)			
Thermal conductivity probe			
Sample culture pH readout	1.2	28	5
Sampling (5 vac., 2 mech. struct. containers, 24 bags)	12.8	323	24
Geology	7.0	46	18
Visual observation			15
Walking (nonassignable)			15
Total Excursion 1	199.9	12,614	120
EXCURSION 2			
Reflectance radiometer	8.0	150	15
Susceptibility bridge	0.7	18	10
Surface temperature loop			12
Thermal conductivity probe			5
Sampling			20
Geology			28
Visual observation			30
Walking (nonassignable)			30
Total Excursion 2	8.7	168	150
Total Flight 1	208.6	12,782	270

Sample Collection and Photography - Sample collection and geologically oriented visual observations and photography are the most important scientific activites to be performed by the astronauts during early surface excursions. The goal is to obtain samples and other data indicative of the homogeneity or inhomogeneity of the lunar surface. Selection of sampling sites will have to be made by visual inspection and will be hindered by lunar lighting and photometric conditions and the necessity to choose sites outside the area contaminated by the landing blast. If the materials in the area accessible to the astronaut appear homogeneous, the problem will be to determine subtle differences prior to sampling. Measurement of the reflectance properties of surface materials at various wavelengths will aid in making these determinations. If a wide variety of rock types is observed, the problem will be to sample representative types. Decisions must be made by the astronaut based on his geological training and experience. Sample sites and all interesting geologic features and phenomena should be photographed. A geology kit and sampling tool package, coupled with the camera equipment, will provide everything required for surface sampling and geologic reconnaissance. Approximately one hour of the 120-minute excursion and 110 minutes of the 150-minute excursion will be assigned for conduct of these tasks.

Scientific Instrument Package - Geophysical information is to be acquired by emplacing an assembly or package of scientific instruments and leaving it on the moon to transmit data. The decision to acquire time-series data over a period longer than the astronaut's stay time on the lunar surface automatically imposes a payload penalty for the concomitant telemetry system and its power supply. Depending on the nature of the measurements involved, the weight of the telemetry system and power supply is between 100 and 150 lb. With a total payload capability of 250 lb, this decision seriously limits the weight which can be alloted to instruments or equipment to be used by the astronaut. Nevertheless, the scientific value of the telemetered data is considered sufficient to warrant inclusion of an emplaced instrument package on the first mission. The recommended package consists of a survey rate meter, surface temperature loop, thermal conductivity probe, low-field helium magnetometer, combination long- and short-period seismometer and recording gravity meter, and a transponder for use as a navigation aid in subsequent location of the package. Because of time limitations, the surface temperature and thermal conductivity measuring devices will be activated during the second excursion; all other instrumentation will be placed in operation during the first excursion.

Second Flight

The second flight will probably consist of four scientific excursions--the first of 120 minutes duration and the latter three, 150

minutes each. For this flight the heavy scientific instrumentation package, designed for long-term monitoring of geophysical phenomena, is replaced by a hand-held drill for sampling the shallow subsurface and various devices for measuring electrical, mechanical and chemical properties of materials. Short geophysical traverses employing gravity, seismic and, possibly, magnetic techniques are proposed. The second flight also differs from the first in that the additional time available permits more walking, and schedules should be flexible enough to permit changes based on the character of the landing area.

First Excursion - The schedule (Table 2) recommended for hazard observation on this excursion is the same as that for the first flight. This procedure is suggested because it cannot be assumed that certain hazards lacking or unimportant at one locality will be of the same significance elsewhere on the surface. Clearly, the recommended schedule should be reviewed thoroughly in the light of the findings of the first flight. These certainly should indicate an order of importance for hazards that were anticipated and perhaps introduce others that were not expected. During the first excursion of the second flight, emphasis is placed on geologic observation, sampling and making measurements with a portable gravity meter. This approach was adopted because the effectiveness of observations and experiments performed during subsequent excursions is dependent upon their relation to the local terrain. Visual observations, sampling and geologic reconnaissance are, therefore, undertaken with a view to planning the measurements and experiments scheduled for later excursions.

Second Excursion - The second excursion is devoted largely to scientific and engineering measurements (Table 2). These involve the use of various instruments for measuring the physical, chemical and mechanical properties of lunar materials.

Third and Fourth Excursions - The third and fourth excursions are devoted primarily to geological, geophysical and compositional observations and measurements allocated on the basis of the character of the lunar surface in the vicinity of the landing site (Table 3). Several different sets of lunar surface conditions can be envisioned, e. g.:

1. Relatively smooth rock surfaces with a thin cover of dust and rubble. Fairly homogeneous material within the astronaut's walking radius.

2. Unsorted rubble and dust of unknown thickness overlying bedrock. Small landforms or surface features not numerous.

TABLE 2

WEIGHT, VOLUME AND TIME REQUIREMENTS FOR MEASUREMENTS, OBSERVATIONS AND EXPERIMENTS FOR EXCURSIONS 1 AND 2, SECOND FLIGHT

	Lb	In.^{3}	Min
EXCURSION 1			
Descent camera	6.0	230	
Descent camera printer (pre-egress)	3.0	320	
Personal dosimeters (2)	0.6	2	
LEM survey rate meter	1.0	70	5
Landing gear thermometer	0.5	4	2
Chemical reactivity detector	0.5	17	10
Boot thermometer	0.5	4	2
Camera and flash	5.3	90	
extra film and flash attachment battery	3.8	64	
Staff penetrometer	2.5	20	4
Tracking transducer	4.5	150	
Gravity meter	7.0	450	5
S[illegible]ple culture pH [illegible]adout	1.2	28	5
S[illegible]pling (8 vac., 2 [illegible]ch. structure, 2[illegible] bags)	51.1	1019	29
Geology	7.0	46	28
Visual observation			15
Walking (nonassignable)			15
Total Excursion 1	94.5	2514	120
EXCURSION 2			
X-ray diffractometer (3 samples)	17.6	1200	15
Probe dielectrometer	2.0	40	10
Vane shear tester	6.0	40	5
Kreisman gauge	9.0	120	10
Gas chromatograph	13.2	690	15
Differential thermal analyzer	10.0	860	10
Erosion particle movement sampler	1.0	35	10
Sampling			15
Geology			20
Visual Observation			20
Walking			20
Total Excursion 2	58.5	2985	150
Total (1 & 2)	153.3	5499	270

TABLE 3

WEIGHT, VOLUME AND TIME REQUIREMENTS
FOR MEASUREMENTS, OBSERVATIONS AND EXPERIMENTS
FOR EXCURSIONS 3 AND 4, SECOND FLIGHT

	Lb	In.^{3}	Min
EXCURSION 3			
Gravity gradiometer	5.0	430	
Tripod for surveying camera	3.6	690	
Portable magnetometer	5.0	140	
Reflectance radiometer	8.0	150	15
Thermal conductivity probe	0.4	4	10
Gravity traverses			55
Sampling			10
Geology and visual observations			15
Walking			45
Total Excursion 3	22.0	1414	150
EXCURSION 4			
Refraction seismic system *	32.0	650	65
Sampling			5
Geology and visual observation			15
Walking			65
Total Excursion 4	32.0	650	150
Total (3 & 4)	54.0	2064	300
Total (1 & 2) (Table 2)	153.3	5499	270
Total Flight 2	207.3	7563	570

*If landforms are well defined, reduce seismic traverses to 15 min and increase sampling to 30 min and geology and visual observation to 40.

3. Terrain irregular with numerous small landforms (e. g., prominences, depressions, fissures) visible through surficial cover.

4. Landforms and surface materials distinct and diverse in nature.

The best landing sites would be within areas characterized by surfaces described in item 1. The Ranger 7 photographs seem to indicate surface conditions akin to those described in items 1 and/or 3. Valid selection of exploration techniques is highly dependent on an accurate portrayal of the lunar surface in proposed landing areas. A smooth, monotonous surface would suggest geophysical experiments and, if feasible, core drilling; a complicated terrain suggests geological observations; differentiated and heterogeneous material suggests geologic observations and compositional determinations.

If the surface is fairly smooth and monotonous, geological and compositional studies which can be undertaken within the 1000-ft walking range of the astronaut will not be especially rewarding and geophysical experiments will be appropriate. The simplest of these would be to read the gravity meter at intervals of 50 ft in two traverses (at right angles to each other) that cross the area within the walking radius of the astronaut. The observed gradients would provide a clue to broad subsurface structure and possibly the deflection of the vertical. Local anomalies would be evidence of shallow subsurface features. A portable seismograph system, such as is used in foundation engineering, might indicate shallow subsurface layering or structure. The compressional wave velocities of the materials might also provide some evidence of their density or composition. If the moon has a magnetic field, a magnetometer traverse should be made at intervals similar to those used in the gravity survey. This can be undertaken in connection with either the seismic line or gravity traverse to determine if the subsurface exhibits variations in magnetic susceptibility.

If, contrary to expectations, the surface at the landing site proves to be irregular, an investigation of the landforms by geological methods will yield more knowledge than will geophysical exploration of the short-traverse type just described. Any evidence of stratification, structure and variation in rock types that can be gathered will be of significance. Geomorphic observations of landform shape, size, orientation, and composition should be made and evidence of modifying processes sought. If heterogeneity in the rocks is observed, it will be important to collect as many samples as possible and to describe the physical properties and field relationships.

Significance in Lunar Resources Exploration

In planning early Apollo missions, measurements concerning properties or phenomena of possible hazard to the astronaut will take precedence over all others. Measurements and experiments not involving hazards are scheduled next in the order of their general scientific interest. Emphasis is placed on those yielding information bearing on the widest range of lunar exploration problems and those providing better results when performed on a manned rather than unmanned mission. Limitations of weight and time are more severe than those of volume. On the first flight, the limiting factor is time; on the second, it is weight. The astronaut will be able to spend only about one hour observing and exploring on the first flight, but passive long-term monitoring of seismic, gravitational, temperature, and radiation phenomena by means of an automated instrument package is proposed.

The combination of time, mobility and logistical constraints dictates obtaining geologic-geophysical data of a single-location and/or limited-time-series nature rather than conducting areal surveys analogous to terrestrial operations. Implanting and activating a scientific instrument package to monitor various phenomena subsequent to astronaut departure greatly extends time-series measurements but obviously does not increase areal coverage. Although the proposed schedules will be greatly modified before the first lunar landing, equipment and instruments required for hazard analysis, geological sampling and observation, photography, passive measurement of geophysical properties and phenomena, and short geophysical traverses will undoubtedly comprise the bulk of early mission scientific payloads.

In view of this scheduling, it is extremely doubtful that adequate data will be available to permit definitive planning of lunar resources surveys until after the first, and possibly second, manned lunar landings. Determination of the physical properties of samples returned to earth from the first mission will be of great assistance in the development of such programs. However, the gross field relationships of these properties and their significance in exploration geophysics will not be clear before the conclusion of the second mission--if then. This situation dictates that only preliminary and tentative evaluations of various geophysical techniques for lunar exploration can be made at the present time.

Preliminary Evaluation of Geophysical Exploration Techniques

Evaluation and selection of geophysical techniques for lunar resources exploration can only be accomplished through consideration of lunar geologic models and the physical properties of associated materials.

Because of our lim' ;d knowledge of the moon, selection of possible geologic models and value ranges of physical property values is rather arbitrary. However, a wide range of possibilities can be covered in the hope that the true lunar situation will be represented by one or more models.

Eight geologic models of lunar surface features or areas were recently defined in an investigation of geophysical techniques for lunar water exploration. They were based on present concepts regarding the origin of lunar surface features and extrapolation of subsurface geology associated with possibly analogous terrestrial forms. Both volcanic and meteoritic impact theories of origin are represented. Eleven rock types were selected for inclusion in the various models. Both extrusive and intrusive igneous rock types were considered, and compositions range from ultrabasic peridotite to highly silicic obsidian. Permafrost and chrondritic materials were also incorporated. The models, two of which are shown in Figures 3 and 4, may be considered to be highly idealized and not necessarily representative of a specific lunar situation. They are proposed as plausible examples whose geologic and physical property contrasts can be used to advantage in evaluating geophysical techniques.

Assigning physical property values to possible lunar rock types necessarily begins with terrestrial values and proceeds to an extrapolation which considers the known or assumed modifying effects of lunar environment and genesis. Data were accumulated for various properties (e. g., density, compressional wave velocity, magnetic susceptibility, electrical resistivity, dielectric constant, and radioactivity) of the selected rock types. Examples of the value ranges for density and magnetic susceptibility are included as Figures 5 and 6.

After assigning pertinent physical property values to the models, responses that would be obtained by a variety of surveys can be estimated by considering differences between properties of the geologic targets and those of the surrounding formations. Promising lunar water exploration techniques were selected by comparison and evaluation of the estimated model responses. In addition, such factors as the following were considered: 1) value of data versus cost of attainment in terms of manpower, weight, power, and volume, 2) probable payload restrictions and 3) other practical difficulties such as implanting electrodes and drilling holes.

Figures 7 and 8 are examples of response comparisons for two models.

Mare Dome Model

The gravity anomaly is large enough to be detected by a gravimeter. A negative anomaly may indicate ice or permafrost; a positive

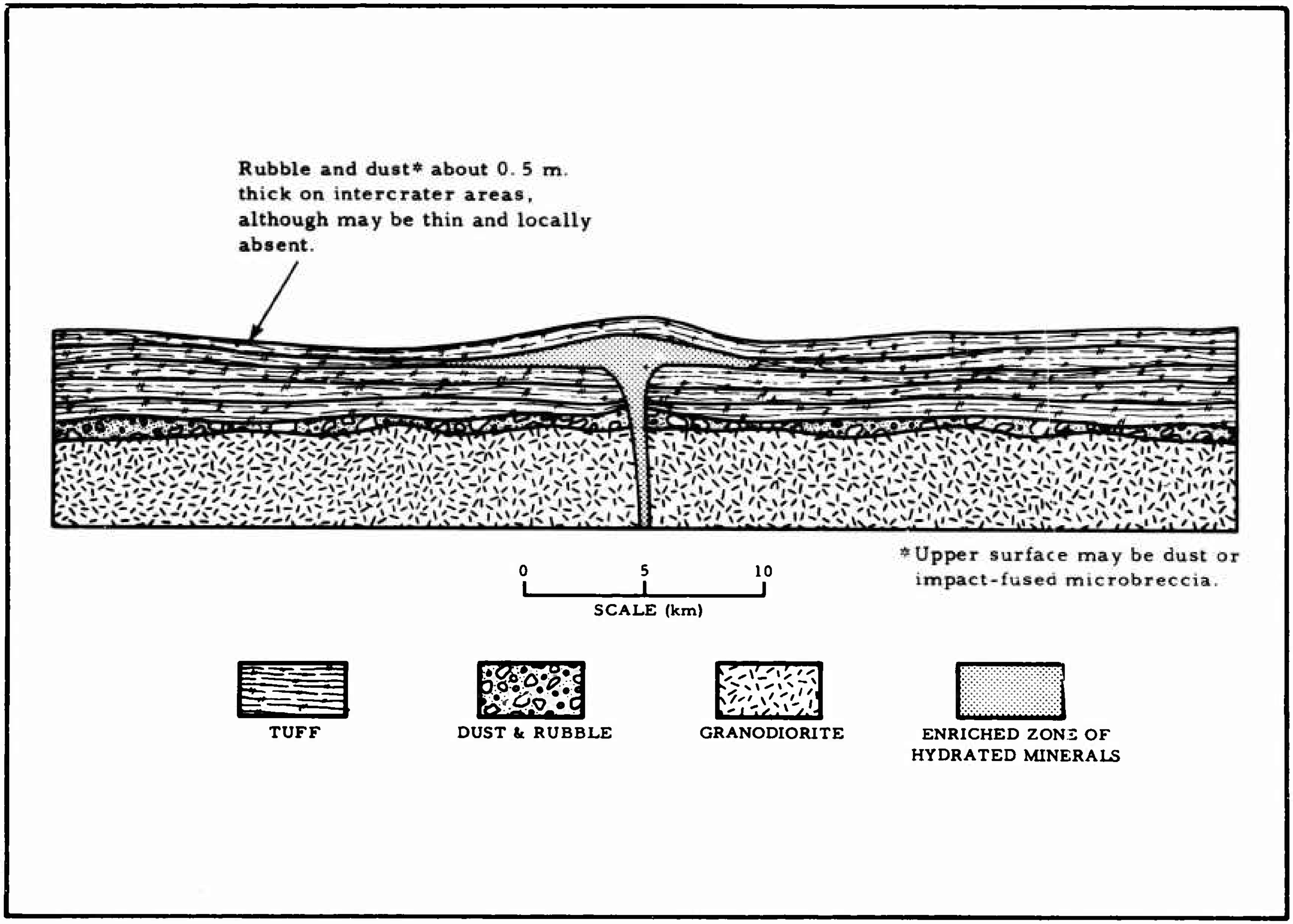

Figure 3. Mare Dome Model

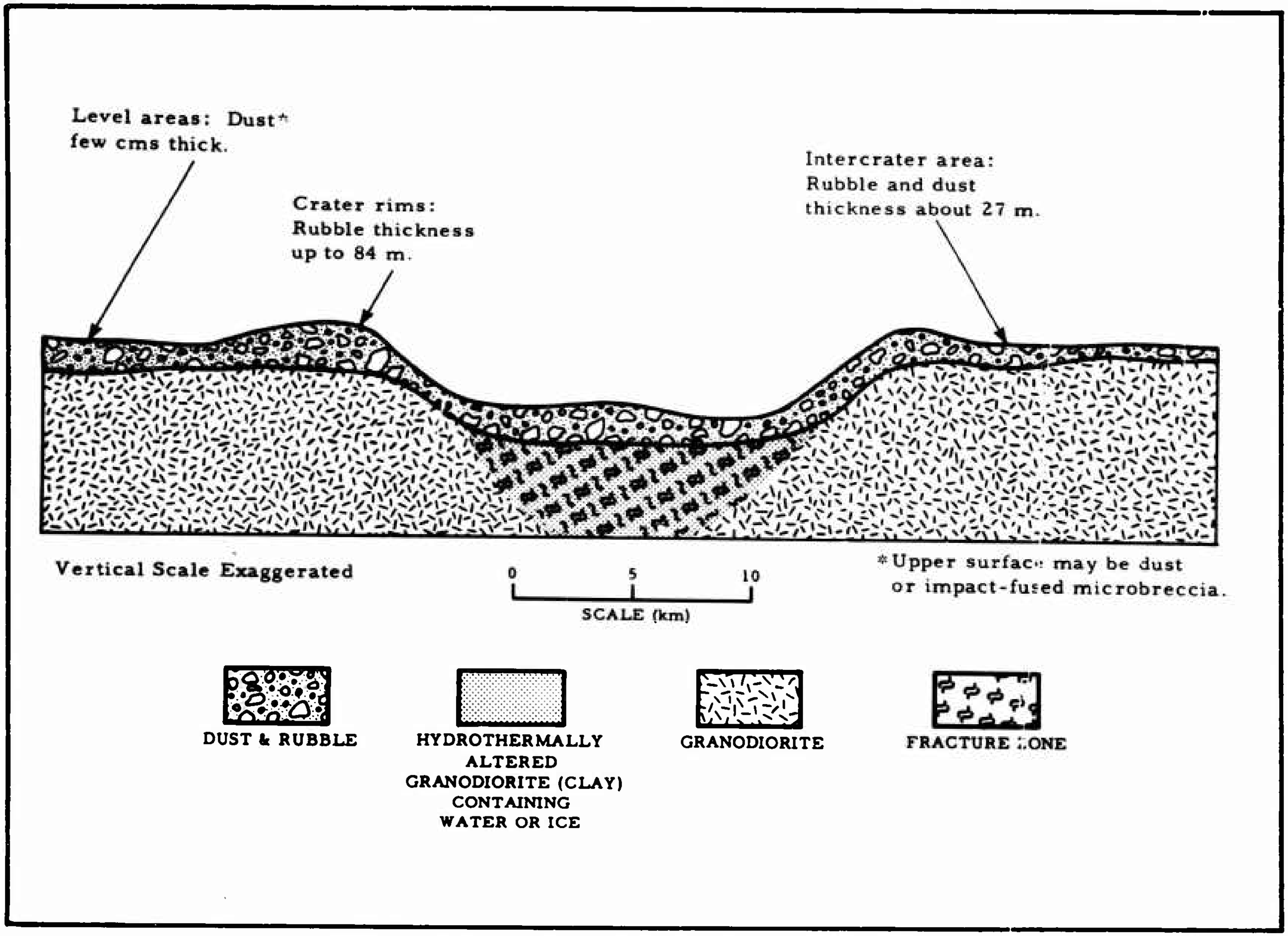

Figure 4. Highland Crater Model

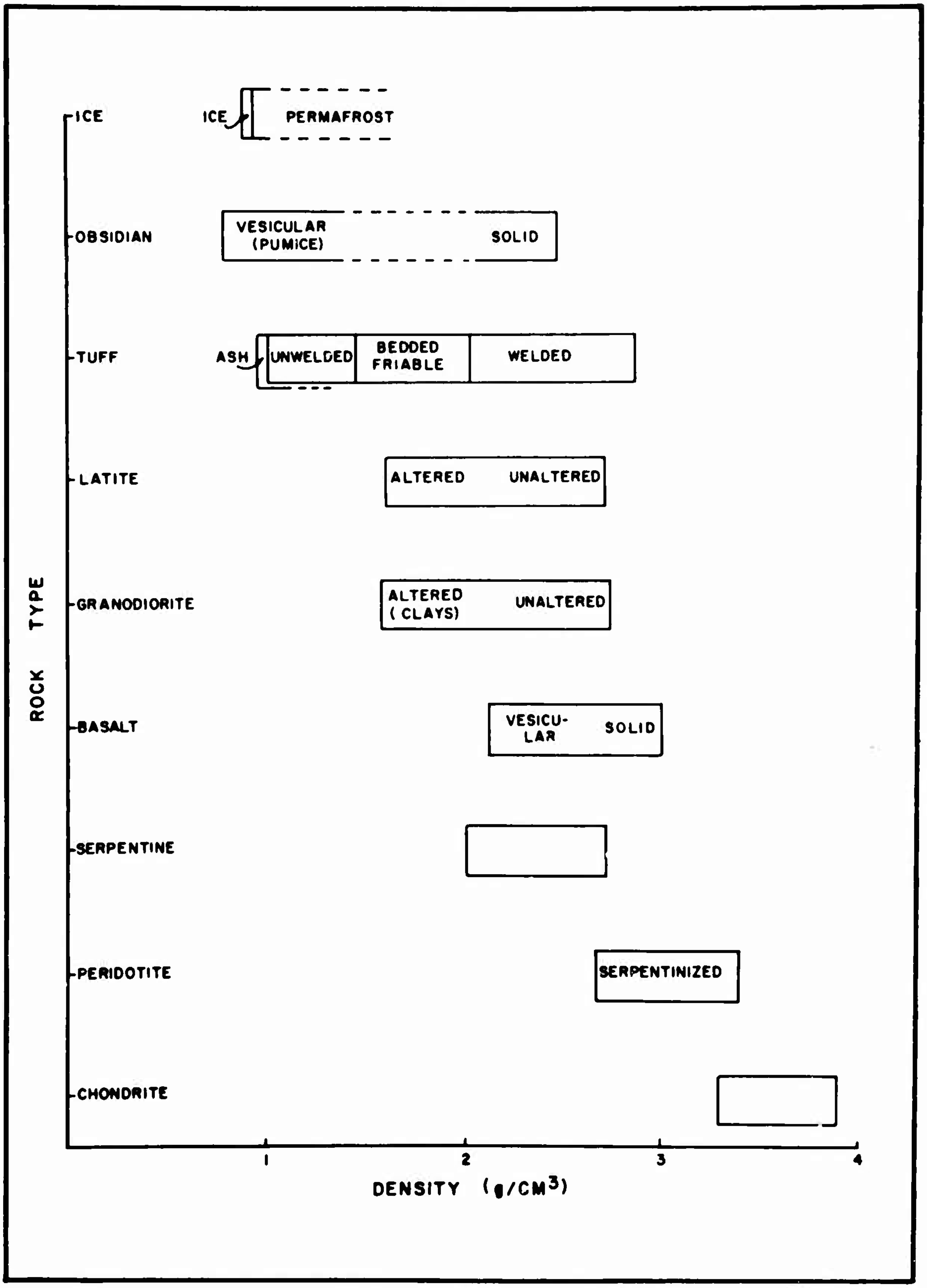

Figure 5. Densities of Rock Types Proposed for Lunar Models (From Westhusing, Crowe, et al, 1964)

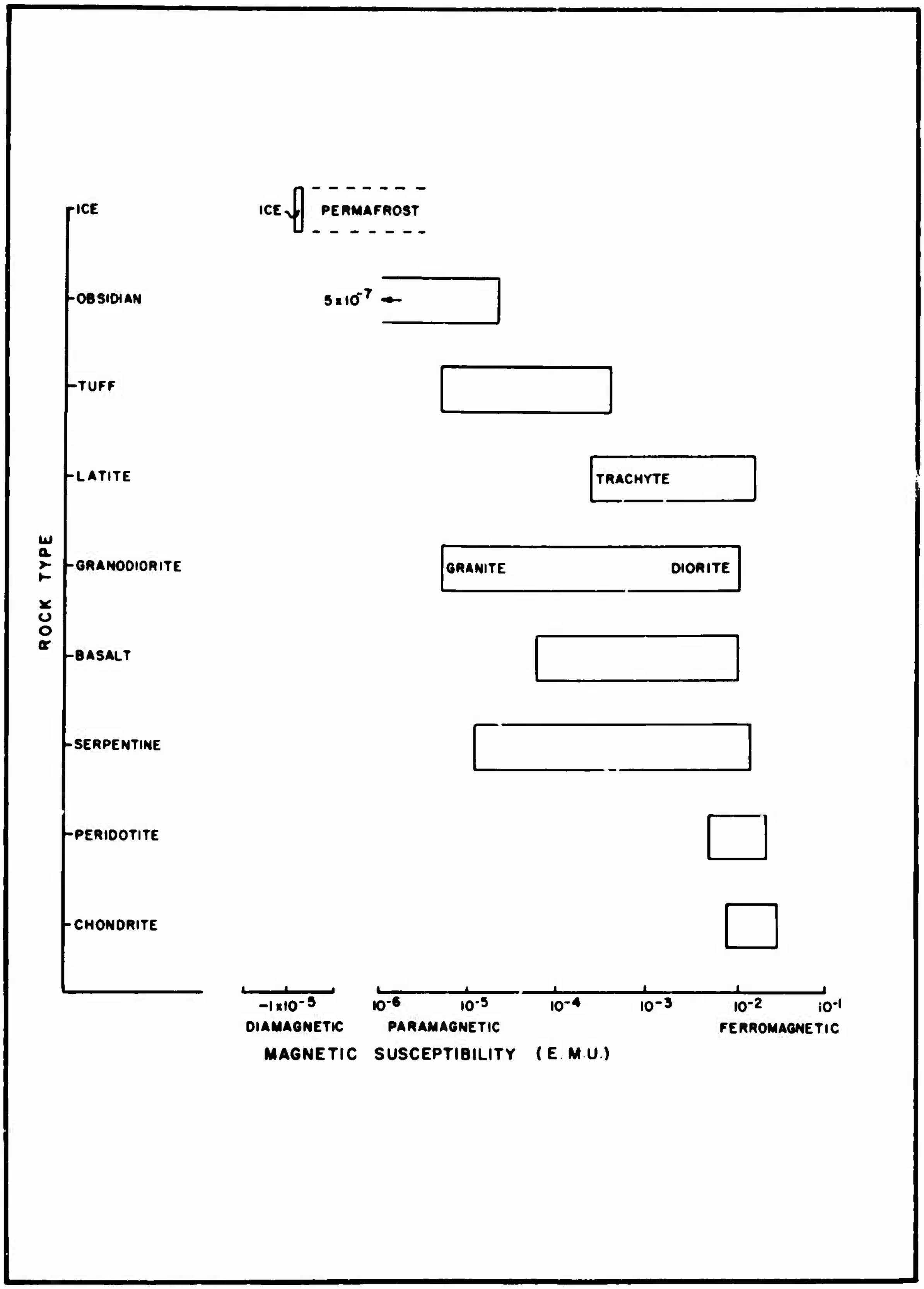

Figure 6. Magnetic Susceptibilities of Rock Types Proposed for Lunar Models (From Westhusing, Crowe, et al, 1964)

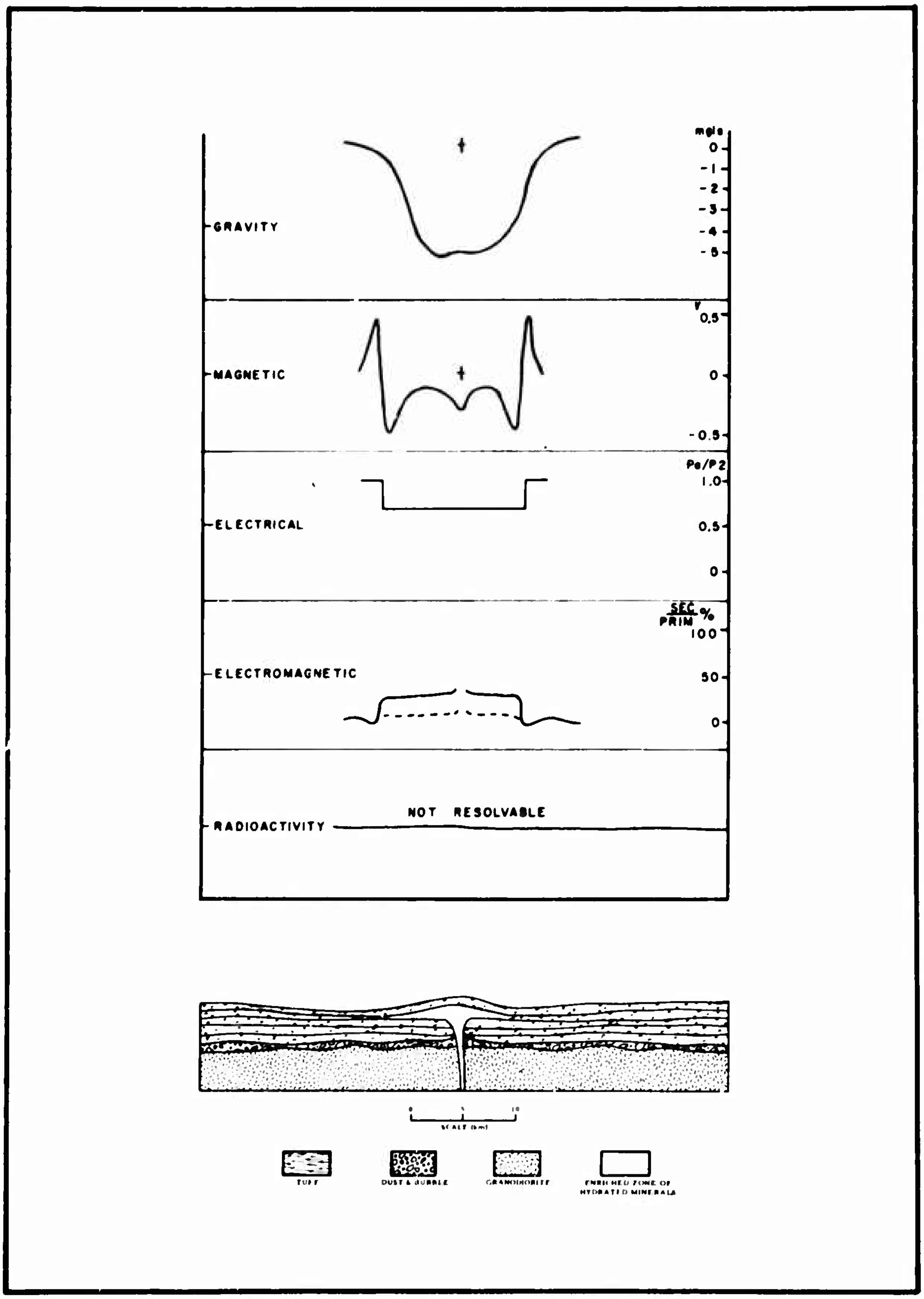

Figure 7. Predicted Geophysical Responses of Mare Dome Model

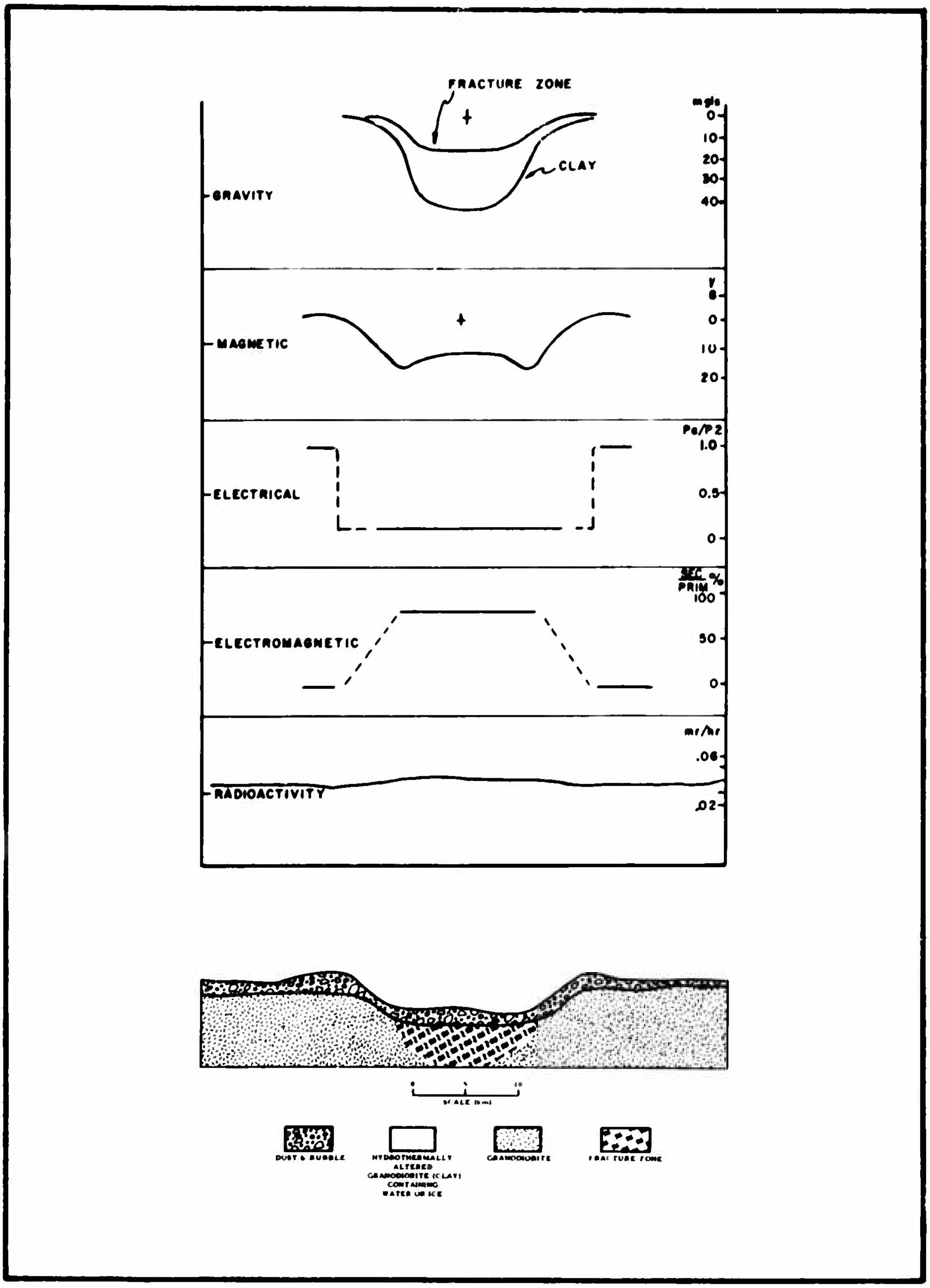

Figure 8. Predicted Geophysical Responses of Highland Crater Model.

anomaly, serpentine. Magnetometer sensitivity would not be high enough to detect the magnetic anomaly. The electrical anomaly is probably too small to be resolved unless the measuring instruments are extremely sensitive. The electromagnetic anomaly is large enough to be detected with a properly designed search coil system. The underlying structure cannot be resolved by radioactivity measurement.

Highland Crater Model

A significant gravity anomaly would occur if clay minerals were present. There will be a detectable negative magnetic anomaly if the magnetite in granodiorite has been hydrothermally altered to pyrite. The electrical and electromagnetic surveys should both detect significant anomalies in this model.

Radioactivity surveys would not provide significant information due to the masking effect of rubble. Difficulties which tend to eliminate the resistivity method from consideration whether or not there is a large anomaly, will be the implanting of electrodes, the large amounts of power required and the problem of measuring the high resistivity of the lunar material if it contains no moisture.

Natural-field techniques evaluated for surface exploration use were natural radioactivity, X-ray excitation, ultraviolet radiation, photography and television, infrared radiation, magnetic, spontaneous potential, and gravity. Artificial-field methods considered were resistivity, induced polarization, electromagnetic induction, and seismic. Gravity, magnetic, resistivity, electromagnetic, and radioactivity methods are especially amenable to prediction of survey profiles across the lunar models. The best combination of these methods to be used in different, postulated lunar situations can therefore be selected. In practice, data provided by such combinations, in conjunction with other geologic methods, are simultaneously interpreted. By defining subsurface structural conditions which satisfy all field observations simultaneously, much of the ambiguity inherent in determinations made by a single method is eliminated.

Of the above-mentioned methods, the following show the highest potential for lunar surface water exploration: gamma-ray (lithologic determinations, fault detection), television (surveying, observation), infrared (thermal mapping), gravity (geologic structure), magnetic (geologic structure) and electromagnetic (conductivity anomalies).

Similar model studies can be conducted for various specific targets or resource materials to aid in the preliminary selection of promising exploration techniques.

Conclusions

The magnitude and success of an extensive lunar exploration program will depend heavily upon the availability and exploitation of indigenous resources. Early manned lunar missions will emphasize hazard analysis; geologic sampling and observation; photography; passive, long-term monitoring of geophysical phenomena and properties; and the conduct of geophysical traverses of very limited length. Significant amounts of geological and geophysical data concerning the shallow lunar subsurface will probably not be available until after the second manned landing. These data will represent a very small areal sample of near-surface lunar conditions,and extrapolation of this information beyond immediate geomorphic boundaries may be quite difficult. Consequently, it is extremely doubtful that definitive planning of lunar resources surveys can be made until the completion of the second landing.

Many studies can be conducted now to assure the shortest possible time lag between completion of early Apollo missions and initiation of a significant program in resources exploration. Mobility, either on or over the lunar surface, is an extremely important factor in survey design, and studies such as those being conducted of manned roving vehicles are sorely needed. Programs involving exploration geophysics, physical property determinations and remote sensing are required. Based on field surveys and laboratory studies, diagnostic geophysical criteria should be developed to distinguish between terrestrial features of meteoritic and volcanic origin. We certainly cannot hope to interpret lunar geophysical data if we do not fully understand phenomena associated with possibly anologous terrestrial forms. Additional emphasis can be given to determining the physical properties of various materials, possibly found on the moon, under the full lunar-day temperature range. Under lunar environmental conditions, physical properties of rocks and minerals may well exhibit values not in agreement with predictions based on terrestrial data. Areal extrapolation of information obtained at a lunar landing site can only be accomplished within a framework provided by photography or imagery obtained by remote sensor systems. It is extremely important, therefore, that the effects of resolution, photographic scale and other changes on the interpretation of aerial and satellite terrestrial photography be thoroughly understood. Geological and geophysical modeling of possible lunar features or areas can aid in the preliminary evaluation of exploration techniques and the design of lunar resources surveys. Such studies are hampered by a lack of data concerning physical properties of materials under lunar environmental conditions and full understanding of geophysical phenomena associated with terrestrial meteoritic impact and volcanic structures.

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DISCUSSION

MR. WINDER: Northrup Lindberg Space Laboratory. You made a comment to the effect that PH measurements were being taken primarily for biologists. Would you care to expand on that?

DR. VAN LOPIK: I think it's mainly important from the standpoint of what might possibly be introduced on (back to) earth, if there were something there. Not that we expect to find anything, but it is one of those things that probably should be done.

DR. SALISBURY: I was wondering why you didn't include an indirect spectroscopic device - the same way you included a sink camera. You mention a need for that. I would emphasize that you spend a lot of time making geological observations, but you have no idea how applicable these are to the moon as a whole, unless you scan this area as you descend, with an indirect spectroscopic device.

DR. VAN LOPIK: I agree with you, Jack. We were supposed to look at "on surface" experiments in this connection and even a descent camera was not something that we were supposed to be looking at. Weight and power limitations are the constraints that throw a lot of these things out. We assigned (weight) values to some two hundred and fifty different measurements, for example, and that was included, and you run it through a computer evaluation type setup and try to fit within the weight, power and volume restraints. If the measurement included one hundred, for example, it has a high figure of merit, something I don't understand about computer programs, but anyway, these things were on the list. It just so happens they didn't get included on the first two flights that I mentioned here. Another one is the micrometeoroid detector problem. Now with the information we had, the detectors were just too heavy. By assigning scientific figures of merit to this, it got dropped out of the first couple of flights.

DR. SALISBURY: Your other measurements are pretty meaningless, unless you have one. I don't know what your computer program knows about scientific merits, but I think this would be appropriate.

DR. VAN LOPIK: The use of infrared spectrometry - O.K. They should be included in the lunar orbit during a manned lunar orbit, thus prior to the landing, taking some measurement of the ground. It's ideal to make measurements somewhere between satellite altitude and when you are actually down on the surface. However, there are constraints with the LEM. It is extremely difficult to get it into the LEM system the way it's set up right now.

SERPENTINE AS A SOURCE OF WATER ON THE MOON: THERMODYNAMICS AND KINETICS OF DEHYDRATION AND THE EFFECTS OF PARTICLE SIZE AND CHEMICAL COMPOSITION

Jon N. Weber
Rustum Roy
Raymond T. Greer

Abstract

If hydrated minerals are found in the lunar crust, serpentine produced by the alteration of olivine rich rocks in the vicinity of fissures through which volatiles released by degassing of the moon's interior may emanate, is the most likely species. Exploitation of such deposits at a reasonable cost will depend upon many factors, among which the temperature and rate of dehydration, and the heat of reaction are important, especially in the design of water extraction facilities. Thirty-three specimens of natural terrestrial chrysotile and massive serpentine were examined, in triplicate, by differential thermal analysis using the Herold-Planje thermocouple apparatus in a controlled atmosphere of P_{H_2O} = 1 atm. Heats of reaction (ΔH) were determined from the area under the DTA curve with a precision expressed by an overall standard deviation of 8 cal/gm. Heats of reaction for specimens which dehydrated quickly and produced sharp DTA peaks permitting more precise construction of base lines, were determined more precisely, with individual sample standard deviations as low as 1.9 cal/gm. Characteristic temperatures, T_c, indicating the start

of the reaction, were reproduced with a standard deviation of about 2° C. Particle size in the ranges 80-100 and -325 mesh (massive serpentines were comminuted by repeated percussion crushing and sieving rather than prolonged grinding) and uncontrolled variation in the degree of packing have relatively little effect on T_c and ΔH, which range respectively from 619° C for white serpentine from Kilmar, Quebec, to 713° C for brilliant sea-green serpentine from Texas, Pennsylvania, and 77.8 to 169 cal/gm. Multiple correlation analysis demonstrates that small amounts of Mn, Cr, and Ti do not influence T_c or ΔH, whereas Ni^{++} and Fe^{++} are weakly correlated with ΔH and strongly correlated with T_c. Serpentine with relatively high concentrations of Ni and ferrous iron (in the order of 1000 and 10,000 ppm respectively) dehydrate at much higher temperatures, but exhibit a somewhat smaller heat of dehydration and a greater activation energy. These relationships are substantiated by statistical tests of significance and explanations are discussed. Average values for ΔH, T_c, and the activation energy in cal/gm, °C, and Kcal are: (1) all serpentines, 106, 659, 95.4; (2) high Ni serpentines (av. 1500 ppm) 101, 674, 112; (3) low Ni serpentines (below 100 ppm) 110, 649, 84.8. Differential thermal analyses of the dehydration of serpentine under high water pressures show that up to 10,000 psi serpentine persists metastably in the stability field of solid dehydration product + water.

Introduction

If serpentine is present on the moon, possibly in the vicinity of fumarolic vents and fissures as Salisbury (1960) has suggested, this mineral with about 14% H_2O may serve as a valuable source of water. If deposits capable of being mined are located, water may be extracted from serpentine after beneficiation by heating the raw material in a device

similar to a tunnel kiln. Because the construction and operation of water extraction facilities on the moon is likely to involve considerable expense, particular attention must be directed to the problem of choosing operating conditions so that the optimum exploitation of hydrous lunar minerals is achieved. In addition to the size and geometry of the furnace and associated reaction vessel, the effect of such variables as the temperature, the ambient pressure of water vapor, and the rate at which new material is added and dehydrated or partially dehydrated material is removed from the furnace must be taken into consideration. To some extent, selection of dehydration conditions will depend on the chemical composition of the serpentine, and conceivably also on the particle size. As Brindley (1964) has emphasized, it is necessary to determine the heat or enthalpy of dehydration (Δ H), the water pressure dependence of the temperature of dehydroxylation, the effects of temperature, water pressure and particle size on the rate of dehydration (reaction kinetics), and the degree to which the chemical composition of the serpentine influences its thermodynamic stability.

Earlier investigations have provided some of this information. Bowen and Tuttle (1949) determined the upper stability limit of serpentine at water pressures above 1000 psi. Water pressure exerted little influence on the temperature at which serpentine decomposed, and extrapolation of their reaction curve to lower pressures would suggest that serpentine should dehydrate at a temperature of about 500° C in the range of water pressure applicable to possible lunar water extraction facilities. On the other hand, numerous dehydration experiments at atmospheric pressure (summarized by Faust and Fahey 1962) showed that temperatures as high as 780° C (e.g.

Van Biljon 1960) were required to liberate water from serpentine; the dehydration reaction at high water pressures is not the same reaction which takes place at very low pressures of water vapor. Using high pressure differential thermal analysis, the relationship between the temperature of dehydration and water pressure applicable to lunar water extraction devices has been defined.

The few published values for the heat of decomposition are not in accord. Sabatier (1954) reported 111 cal/gm, Mchedlov-Petrosyan (1953) obtained 40.7 cal/gm, and Ando et al. (1957) found a range of values extending from 40 to 110 cal/gm. Using differential thermal analysis, values of ΔH were determined for 33 specimens of serpentine, and the effects of chemical composition were evaluated.

Experimental

The thermocouple arrangement similar to that described by Herold and Planje (1948) consists of a platinum capsule 2.5 mm in diameter and about 15 mm long, open at one end, and containing about 10 mg of sample. A sealed capsule of similar dimensions, filled with Al_2O_3, serves as the "reference standard". The capsules are connected by a wire of Platinel thermocouple alloy (Accinno and Schneider 1960) welded to the capsule walls. In this arrangement, the capsules themselves serve as the thermocouples. Theoretical analysis of the heat transfer by Sewell (1952, 1955) has demonstrated that the area under the DTA peak is proportional to the heat of reaction per unit mass of reacting material, and that the peak area is independent of the heating rate provided it is linear, the rate at which the reaction takes place, and the specific heat of the sample.

To a first approximation, the peak area is also independent of the thermal conductivity of the sample.

The thermocouple arrangement is mounted in a 2" O.D. stellite pressure vessel in which water pressures from 15 psi to 20,000 psi can be generated and measured. The noble metal Platinel thermocouple alloys provide an emf similar to that of chromel-alumel, and the voltage from the differential couple is amplified with a solid-state d.c. Acromag amplifier with a noise level of 1 microvolt and drift of about 5 microvolts.

ΔH measurements were obtained from the area under the DTA curve using a calibration curve constructed from peak areas obtained by fusion and/or inversion of a variety of compounds with known heats of reaction. The heating rate, about 10° C/min, was shown to be linear over the temperature range in which serpentine decomposed.

The value of kinetic data obtained from differential thermal analysis is limited by three factors: (1) the temperature is changing while the reaction is taking place, whereas ideally, isothermal dehydration methods such as weight loss techniques provide more reliable and precise kinetic data, and in addition, provide some information concerning the reaction mechanisms. (2) The concentrations of the reactants and products at any given time are determined indirectly by temperature difference (between a sample and the reference standard) resulting from heat transfer during the reaction. Since heat transfer is not instantaneous, precise determination of concentrations is not possible. (3) It is necessary to assume that an equation relating the rate of change in concentration of the reactant to the concentration of the remaining reactant is a reasonable description of reality; such factors as the shape of the reactant particles

are not taken into account. Some of the difficulties have been evaluated and are discussed by Borchardt (1957), and Borchardt and Daniels (1957). Among the most important assumptions inherent in the determination of rate constants from DTA are: (1) the temperature of the reactant is uniform, (2) the area under any appreciable portion of the DTA curve is proportional to the heat absorbed during the time interval in which that portion of the DTA curve was recorded, and this quantity of heat is in turn proportional to the mass of the sample which reacted during this time, (3) the kinetics of the reaction can be described by a single rate constant, and (4) the activation energy does not vary with temperature during the reaction.

The strongest support for the value of kinetic data derived from differential thermal analysis was provided by Tsuzuki and Nagasawa (1957). These authors obtained weight loss curves and DTA curves from the same samples. Kinetic parameters calculated from weight loss data were used to construct theoretical DTA curves for comparison with DTA curves obtained by actual experiment. They conclude that the DTA curve faithfully follows the change in decomposition rate, except for a slight difference in peak temperatures.

Assuming a relationship between the rate of reaction and the concentration of remaining reactant: $-dc/dt = k\,c^n$, where dc/dt is the change in concentration of reactant with time t, c is the concentration of the unreacted sample, k is the rate constant and n is the order of reaction, k can be determined if n is known, and if measurements of dc/dt and c are available. The latter can be obtained from relative areas under different portions of the DTA curve. Using the Arrhenius equation, $k = A\,e^{-E/RT}$,

where E is the energy of activation, A is a constant, R is the gas constant and T is the absolute temperature, it is possible to determine both k and n by a digital computer program which calculates a set of k values for each set of dc/dt and c measurements, using an arbitrary value for n. The value of n which provides the best fit of the concentration data to the Arrhenius equation is taken as the observed order of reaction. In practice, up to 20 measurements of dc/dt, c, and T* are taken from each DTA curve, and 21 sets of log k vs 1/T values are computed for values of n ranging from zero to 4.0, in 0.2 increments. Linear regression lines are automatically drawn for each set of log k vs 1/T values, correlation coefficients are computed, and the most linear plot is the criterion used in selecting n. The activation energy is computed from the Arrhenius equation.

Quantitative spectrochemical analyses were made for Fe, Mn, Ti, Ni, and Cr using cobalt as an internal standard. Details of the method are described by Joensuu and Suhr (1962). Ferrous iron was determined by $KMnO_4$ titration.

<u>Discussion of experimental variables</u>

(1) <u>Effect of particle size on reaction temperatures determined by differential thermal analysis</u>

A number of authors have demonstrated a relationship between the DTA temperature of dehydration and the particle size of serpentine samples; recent studies include Martinez (1961), Veniale (1962) and Hoyos and Delgado

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* The temperature of the sample. This is obtained by subtracting the temperature difference between the sample and reference capsules (determined from the height of the DTA curve above the base line) from the temperature indicated by the recording thermocouple.

(1961). Although very fine particles will dehydrate at somewhat lower temperatures than material with coarser micelle size, it appears that the effect of particle size as such has been somewhat overemphasized. Bayliss (1964) carefully prepared size fractions of high-purity calcite by repeated gentle tapping and sieving, an attempt to comminute by separation along cleavage planes without generating appreciable structural damage. DTA curves obtained from the dissociation of $CaCO_3$ in a controlled atmosphere of CO_2, and with a heating rate of 15° C/min, were identical. Size fractions as coarse as 35 to 48 mesh indicated the same dissociation temperature as samples whose particles ranged in size between 1.6 and 1.16 microns. Variations in the temperature of dissociation are attributed by Bayliss to variations in the degree of structural damage produced in the grinding process.

Samples of massive serpentine used in this study were reduced to -325 mesh by repeated percussion crushing and sieving. Fibrous varieties were emplaced in the platinum capsules without any attempt at size reduction.

(2) Sample purity

Since peak areas are associated with a measured weight of sample to determine the heat of reaction, the presence of extraneous phases will cause erroneous, low values of ΔH. An impurity amounting to 1% will inject an error of about 1% in ΔH determinations. Serpentine minerals are seldom found in experimentally useful quantities without associated minerals such as magnetite, chromite, etc. Serpentine derived from the alteration of ultrabasic rocks, for example, will contain inclusions of iron oxide

minerals since relatively little iron of the original olivine enters the serpentine structure. Samples used in this study were broken into +20 mesh fragments and hand-picked under the binocular microscope. A small quantity of the selected material was examined by X-ray diffraction, several milligrams were used for spectrochemical analysis, and the remainder was consumed by chemical analysis for Fe^{++} and by differential thermal analysis.

(3) Errors associated with differential thermal analysis

Small variations in packing of the sample, position of the thermocouples in the furnace, heating rate linearity, and experimental errors involved in measuring temperatures and areas under the DTA curve were evaluated by replicate analysis of several samples. The observed standard deviations for measurement of the characteristic temperature (temperature at the point where the baseline intersects the tangent drawn at the point of maximum slope of the DTA curve) and heat of reaction are 2° C and 8 cal/gm respectively. Construction of the base line introduced the greatest source of error in ΔH determinations; for certain specimens with sharp DTA peaks, the standard deviation of ΔH determination was as low as 1.9 cal/gm. All samples were examined by DTA in triplicate.

Results and Discussion

(1) The Dehydration temperature of serpentine

(a) Effect of water pressure

Two specimens of serpentine were selected for experimental determination of the pressure-temperature dehydration curve: (1) Massive, dark-green serpentine from Cardiff, Maryland (LV-8), and (2) Massive, light-green serpentine from Balmat, New York (LV-9). X-ray diffraction

was used to show that extraneous phases were absent.

Pressure-temperature data are presented in figures 1 and 2. LV-8 (fig. 1) dehydrates at about 650° C at lower pressures of water vapor, and the decomposition temperature increases with increasing pressure to about 775° at approximately 10,000 psi. Above this pressure, lower dehydration temperatures are encountered. The reaction curve for LV-9 (fig. 2) is similar to that of LV-8, but is displaced to lower temperatures. At 100 psi, LV-9 dehydrates at about 610° C, while temperatures around 710° are required to decompose this sample at water vapor pressures in the vicinity of 10,000 psi. As in LV-8, dehydration at pressures above 10,000 psi takes place at lower temperatures.

In figure 3, pressure-temperature reaction curves for LV-8 and LV-9 are compared with the pressure-temperature curve for the upper stability limit of serpentine, as determined by Bowen and Tuttle (1949). Under dehydration conditions applicable to the processing of serpentine on the moon, this mineral persists metastably in the stability field of solid product + water at water pressures below about 10,000 psi. Temperatures in the range 600 to 800° C, therefore, must be attained in proposed dehydration kilns. Above 10,000 psi, the catalytic effect of water lowers the temperature limit at which metastable serpentine can exist as shown by pressure-temperature points in the upper right of figures 1 and 2. At the highest water pressures attained in these experiments, i.e. 18,500 psi, the dehydration temperature is still over 600° C.

The relative positions of the pressure-temperature curves for LV-8 and LV-9 in figure 3 are attributed to differences in chemical composition.

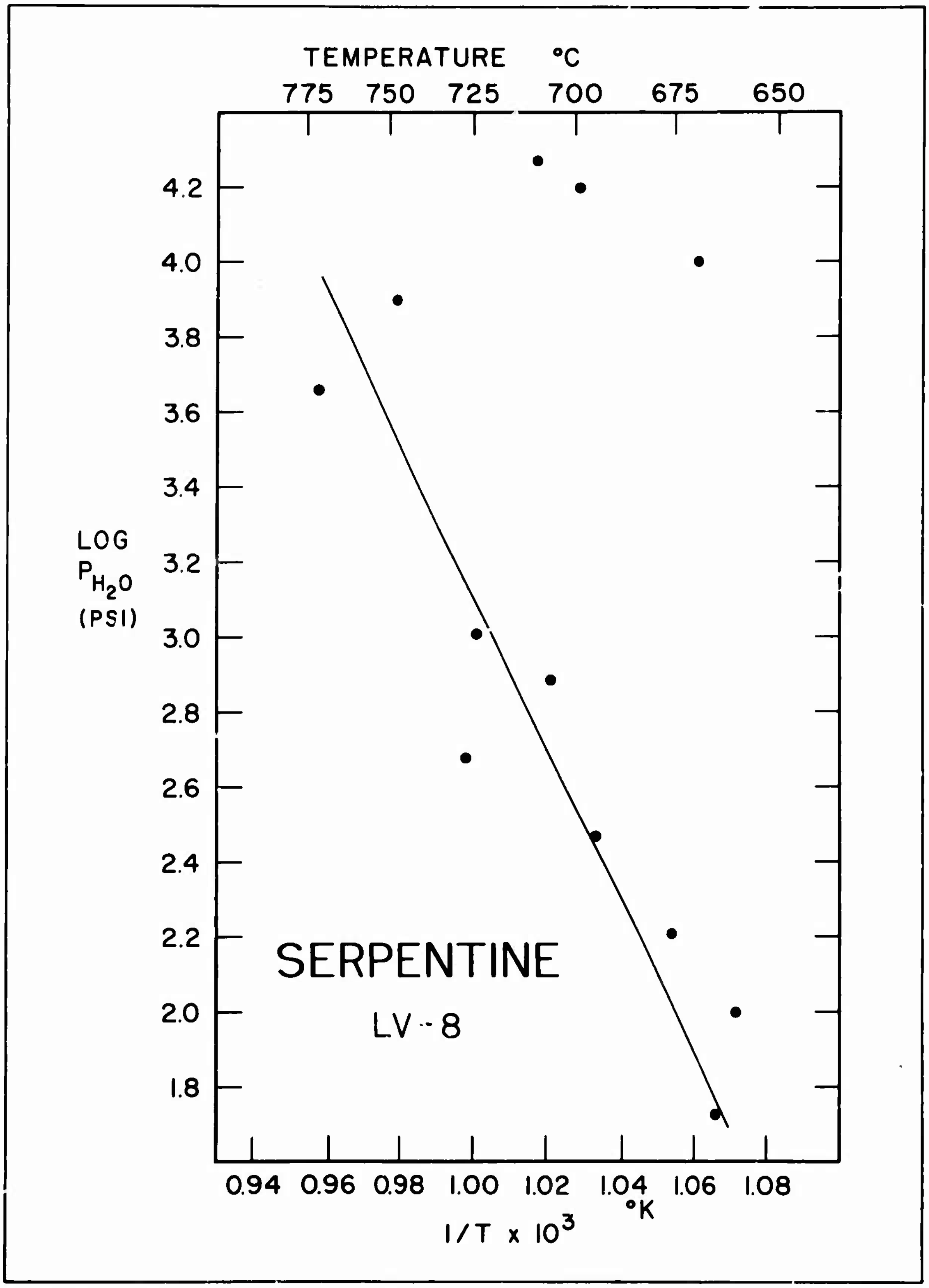

Figure 1. Pressure-temperature dehydration curve for a high-nickel serpentine.

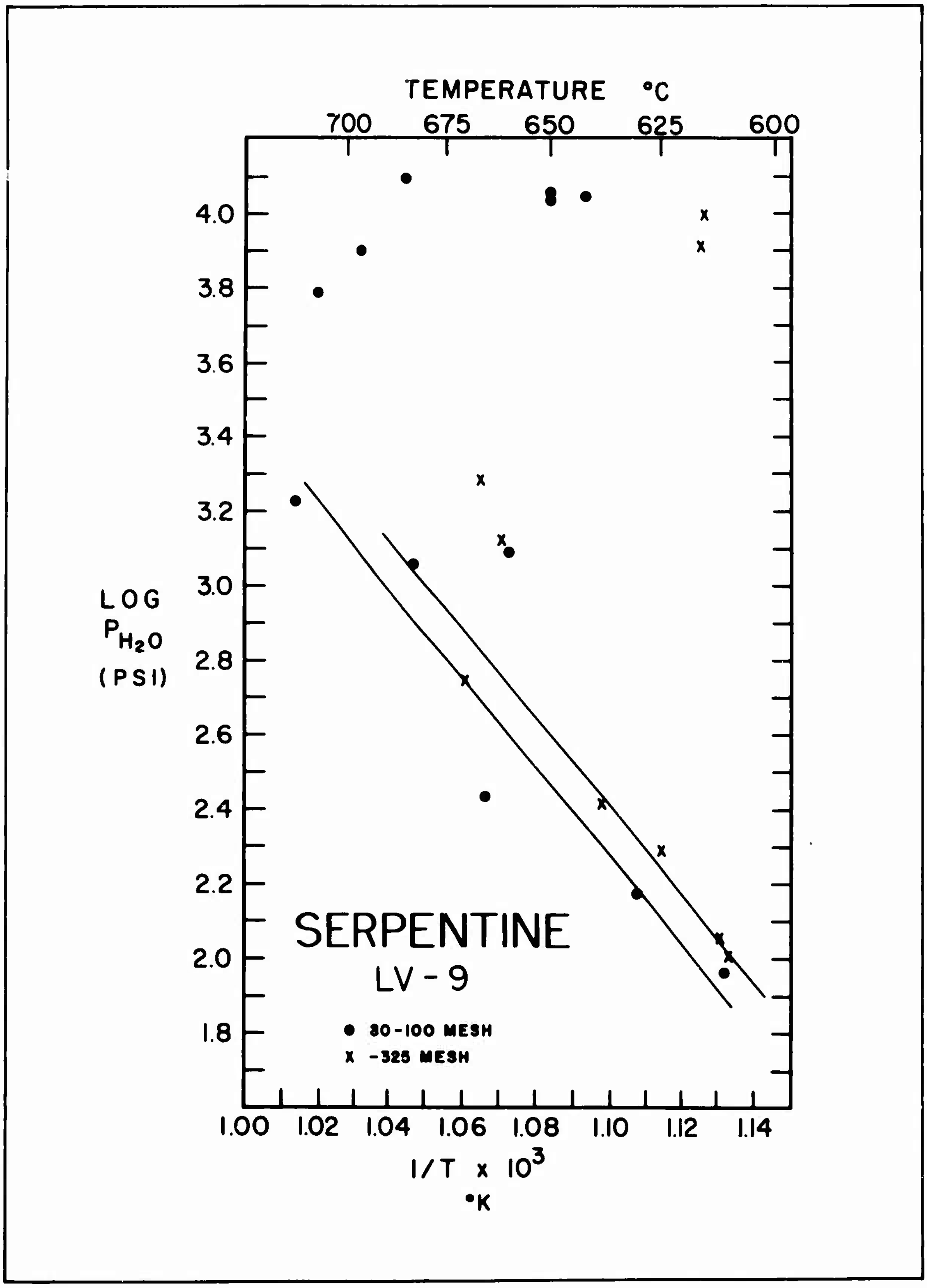

Figure 2. Pressure-temperature dehydration curve for a low-nickel serpentine.

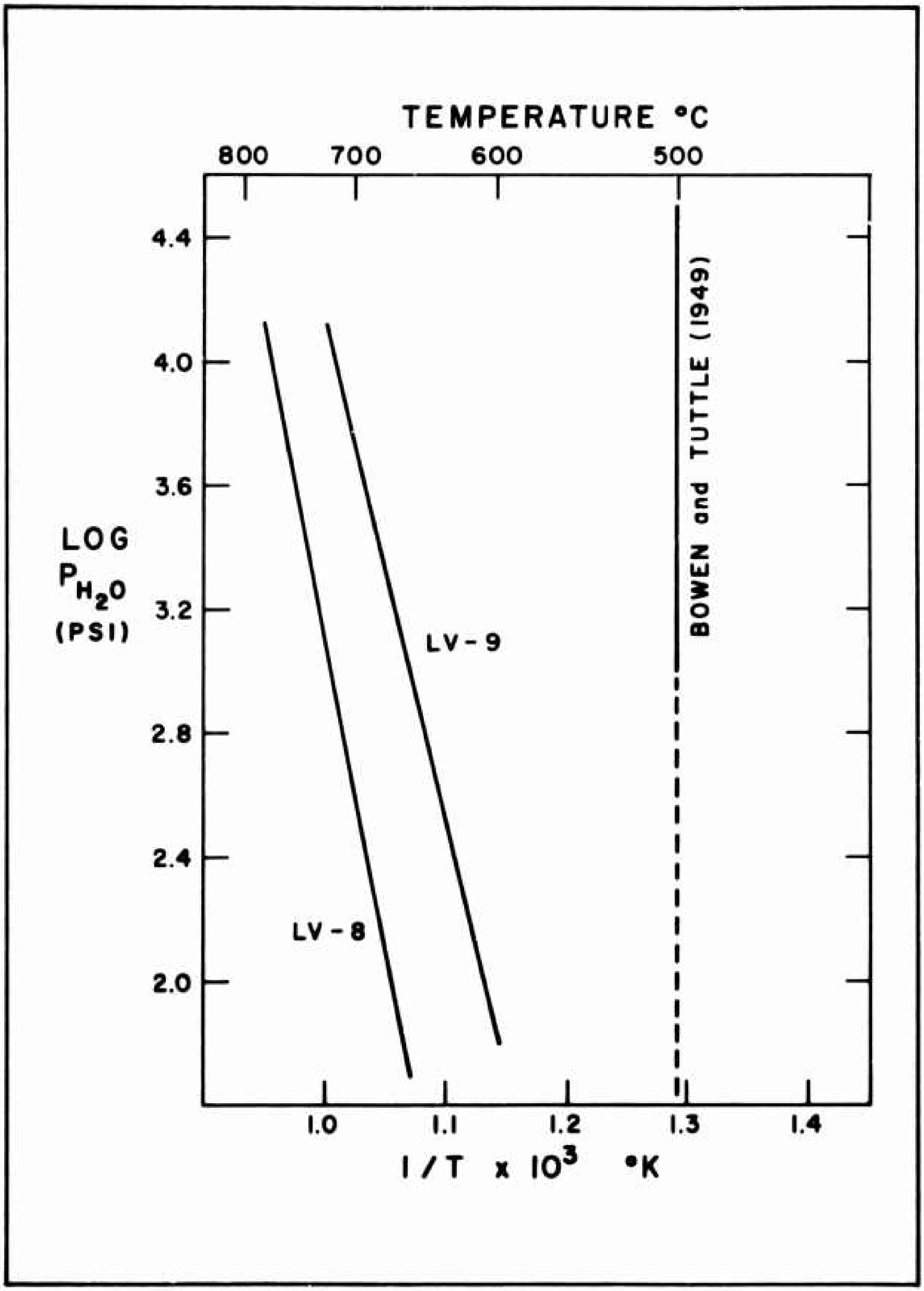

Figure 3. Comparison of the upper stability limit for serpentine (Bowen and Tuttle) and pressure-temperature dehydration curves for serpentines LV-8 and LV-9.

(b) The effect of grain size

The effect of grain size on the dehydration temperature has been the subject of much attention. Hoyos and Delgado (1961) and Martinez (1961) demonstrated that the dehydration temperature of serpentine at atmospheric pressure decreased with decreasing particle size. Bayliss (1964), however, showed that the reaction temperature determined by DTA is influenced by the degree of crystallinity and not by the particle size unless the latter is connected with the degree of crystallinity, that is, when deformation of the crystal structure is induced in the process of obtaining fine grain sizes.

To investigate the effect of particle size, two size fractions of LV-9 were obtained by repeated percussion comminution and sieving. In figure 2, two possible reaction curves might be distinguished below 10,000 psi. As expected on the basis of the experiments of Martinez, dehydration temperatures for 80-100 mesh serpentine appear to be somewhat greater than those for the -325 mesh fraction. Statistical analysis of covariance, using the data obtained below 10,000 psi, indicates that (1) the two populations* have homogeneous variance, (2) the regression coefficients are not significantly different at the 1% level of significance, and (3) the regressions are equivalent at the 1% level. The probability, that the apparent difference in the p-t curve resulting from particle size is fortuitous and not real, is very high. Any effect of particle size is, therefore, masked by experimental error.

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* Each population is bivariate, consisting of pressure and temperature measurements for a given particle size of sample LV-9.

(c) Effect of chemical composition

Thirty-three different specimens of serpentine were studied by DTA at $P_{H_2O} = 15$ psi to determine the relationship between the decomposition temperature and chemical composition. The relationships are expressed by correlation coefficients (r) in the matrix of Table 1, where:

$$r = b\,(s_x/s_y)$$

$$b = \text{linear correlation coefficient} = \frac{\sum x_i y_i - \frac{\sum x_i \sum y_i}{N}}{\sum x_i^2 - \frac{(\sum x_i)^2}{N}}$$

$$s_x = \sqrt{\frac{\sum x_i^2 - \frac{(\sum x_i)^2}{N}}{N-1}}$$

$$s_y = \sqrt{\frac{\sum y_i^2 - \frac{(\sum y_i)^2}{N}}{N-1}}$$

for any two variables, x and y, for N samples.

Chromium, titanium and manganese are not correlated with the decomposition or "characteristic" temperature, T_c, but positive correlations of Ni and Fe with T_c are evident. Summary statistics, presented in Table 2, show that the 13 high nickel serpentines (average 1500 ppm Ni) exhibit a much higher characteristic temperature of dehydration (675° C) than the group of 18 serpentines whose nickel content is below 100 ppm ($T_c = 649°$ C).

The stability of serpentine is influenced largely by the degree of mismatch between the octahedral brucite layer and the adjacent tetrahedral Si-O sheet, imperfect matching resulting from the different dimensions of the two layers. Better matching of the octahedral and tetrahedral layers can be achieved by the formation of a tubular structure with the brucite layer on the convex side of the curve (variety chrysotile), by isomorphous substitution of larger cations for Si or smaller cations for Mg providing a corrugated or platy structure (varieties antigorite and lizardite).

The substitution of Ni and Fe^{++} for Mg in the serpentine structure results in greater interlayer bond strength arising from the greater percentage of covalency in Ni-O bonds compared to Mg-O bonds. The effect of nickel substitution for magnesium on the stability of serpentine was demonstrated with synthetic materials prepared by Roy and Roy (1954). The upper stability temperature reported by these authors for Ni-Si serpentine is 530° C compared to 490° C for Mg-Si serpentines.

In addition to the correlation of Fe^{++} and Ni with decomposition temperature for serpentines dehydrated under a water pressure of 15 psi, the relative positions of the pressure-temperature dehydration curves for LV-8 and LV-9 in figure 3 can be related to chemical composition. Decomposition temperatures of LV-8 (3.30% FeO, 0.19% NiO) are higher for a given water pressure than those of LV-9 (0.05% FeO, <0.02% NiO).

(2) Heat of dehydration

Multiple correlation analysis (Table 1) revealed a number of relationships between the heat of reaction, the decomposition temperature and the chemical composition. At the one percent level of significance, a striking

TABLE 1

Matrix of correlation coefficients (r)

	T_c	T_p	n	E	total Fe	FeO	Mn	Cr	Ni	Ti
Δ H	-.59	-.57	-.31	-.38	-.17	-.22	-.07	.12	-.28	-.04
T_c		.91	.57	.78	.26	.38	-.05	.21	.65	-.22
T_p			.70	.67	.25	.34	-.08	.22	.75	-.00
n				.73	.28	.29	.14	.21	.69	.14
E					.31	.39	.16	.30	.51	-.20
total Fe						.70	.08	.33	.31	.11
FeO							.20	.39	.28	-.01
Mn								-.16	-.24	.08
Cr									.37	-.08
Ni										-.01

T_c = characteristic temperature

T_p = peak temperature

Values of r greater than .449 and .349 are significant at the 1% and 5% levels respectively.

TABLE 2

Summary statistics for the dehydration of serpentine

	No. of specimens	Characteristic temperature °C		ΔH cal/gm		Ni content ppm	
		Av.	s.d.	av.	s.d.	av.	s.d.
Fibrous serpentines	12	670	13.5	96.3	11.7	790	838
massive serpentines	21	653	27.9	112	24.6	513	1000
All serpentines	33	659	24.9	106	21.9	613	942
High nickel serpentines (Av. 1500 ppm Ni)	13	675	23.7	101	21.6		
Low nickel serpentines (below 100 ppm Ni)	18	649	21.4	110	22.8		

s.d. = standard deviation

TABLE 3

Heat of reaction and nickel content of massive serpentines with 1000 ppm or more of nickel

Nickel, ppm	ΔH, cal/gm	Characteristic decomposition temperature, T_c °C
1000	157	636
1150	121	666
1400	101	689
1400	90	701
4300	78.9	713

inverse correlation is substantiated for ΔH and T_c, that is, samples which decompose at higher temperatures tend to have a lower heat of reaction. Chromium, titanium and manganese are not correlated with ΔH, but a negative or inverse correlation of nickel and iron with ΔH is evident. The mean ΔH for the high nickel serpentines (mean Ni content 1500 ppm, mean ΔH 101 cal/gm) is lower than the average heat of reaction for the low nickel group (less than 100 ppm Ni, mean ΔH 110 cal/gm). Evidence that this difference is real is provided by the student-t test of means at the one percent level of significance. The variation of ΔH with T_c and nickel content is illustrated in Table 3 in which data for all of the massive serpentines containing 1000 ppm or more of nickel are listed.

These relationships may be explained with the aid of a number of chemical analyses, considered to be highly reliable, which have been collected by Deer, Howie and Zussman (1962), Faust and Fahey (1962) and Bates (1959). After calculation of the number of ions on the basis of 9(O,OH), several relationships emerge: (1) the sum of the tetrahedral cations (Si,Al,Fe^{+3}) for samples classified as chrysotile and lizardite is somewhat below the ideal value of 2, and the number of (OH) ions is greater than the value of 4 required by the ideal formula of serpentine, (2) for samples classified as antigorites, Σ octahedral, Σ tetrahedral, and Σ OH are much closer to the stoichiometric values, (3) in chemical analyses, Ni is more often reported in antigorites, although exceptions are known, (4) nickel-rich serpentines usually contain less (OH) than specimens with lower nickel contents, (5) for many chrysotile analyses, there are more (OH) ions than the number required to balance (by substitution for O in the Si-O tetrahedra) the charge deficiency

caused by substitution of Al and Fe^{+3} for Si.

Several reliable analyses are remarkably anomalous, for example, the chemical composition of the serpentine from the Shetland Islands reported by Brindley and von Knorring (1954). McConnell (1954) suggested that the excess (OH) ions were present in the tetrahedral layer and demonstrated that the analysis of Brindley and von Knorring could be recast in a formula different by less than 1 percent from the stoichiometric formula by including (H_4) in the Si-O layer. On the basis of 4(OH), the sum of Si (1.75), Al (0.01) and H_4 (0.24) is 2.00, and the charges are balanced. It appears that for the chrysotiles, and perhaps the lizardites as well, tetrahedral cation deficiences possibly caused by insufficient Si cations are balanced by appreciable substitution of OH ions. As Bates (1959) points out, this arrangement would weaken the structure and require a tubular or corrugated habit. The stability of this polymorph would be slightly lower than serpentine with a greater ratio of tetrahedral to octahedral cations, which requires no or less (OH) substitution and which would exhibit a platy habit.

A review of a large number of thermal analyses of serpentine by Faust and Fahey (1962) indicates that platy serpentines identified as antigorite dehydrate at higher temperatures than the tubular and corrugated varieties. DTA peak temperatures for antigorite are generally above 750° C, whereas endothermic peaks for specimens of chrysotile and lizardite appear between 680 and 750° C.

It appears then, that the larger values of ΔH apply to specimens with a greater quantity of hydroxyl ions in the serpentine structure. These specimens, because of a weakened structure resulting from appreciable

substitution of OH ions would exhibit a tubular or corrugated structure and would decompose at lower temperatures. Substitution of nickel for magnesium results in increased stability, probably a platy structure, and hence higher temperatures of dehydration. Since many natural serpentines are shown by electron microscopy to be mixtures of chrysotile, lizardite and antigorite, a gradation from serpentine characterized by low nickel, high ΔH, low decomposition temperature to serpentine characterized by high nickel, low ΔH and high dehydration temperature is to be expected, and the isomorphous substitution of other elements will result in some deviation from precise relationships between these variables.

(3) Reaction Kinetics

The mean value for the order of reaction, n, is 0.93, but the standard deviation of 0.62 indicates considerable variation from sample to sample. The activation energy (average 95.4 Kcal/mol; standard deviation 30.1) exhibits similar variation. Triplicate analysis shows that these differences are characteristic of the sample and are not caused by experimental error. Such large variations are not observed for other minerals studied with the same apparatus. The matrix of correlation coefficients of Table 1 shows that the activation energy is negatively correlated with ΔH, and positively correlated with the dehydration temperature ($r = 0.78$), the ferrous iron content, the concentration of nickel and the order of reaction. This would indicate that at equivalent stages of the reaction (i.e. concentration of remaining reactant) the

structure of the weaker low nickel varieties is decomposing at a greater rate than the structure of the high nickel serpentines.

Summary

Under conditions similar to those proposed for water extraction facilities on the moon, the dehydration of serpentine requires temperatures considerably greater than the temperature above which serpentine is not a stable phase. The dehydroxylation temperature of metastable serpentine increases with increasing water pressure until about 10,000 psi, above which the catalytic effect of water permits decomposition at lower temperatures. At water pressures much above 15 psi, grain size in the range -325 mesh to 80 mesh appears to have little effect on the decomposition temperature. Resulting from greater stability, the pressure-temperature curve of serpentine containing appreciable nickel and ferrous iron isomorphously substituting for Mg is displaced towards higher temperatures at a given pressure. The heat of dehydration is larger for low-nickel serpentines and for serpentines which dehydrate at lower temperatures at a given pressure. Variations in Δ H are ascribed to differences in the hydroxyl contents which in turn influence the stability of the serpentine structure. Kinetic and thermodynamic data for a given variety of serpentine can be used with the equation derived by Brindley (1964) to determine the optimum operating conditions for lunar water extraction facilities.

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DISCUSSION

MR. JIM MALCOLM: How about the reversability of this dehydration?

DR. WEBER: We have never been able to get a reversability reaction on the metastable dehydration, only on the stable dehydration which was obtained at a very high pressure. But, we obtained, as a reaction product, an amorphous phase and this would not crystallize in a reasonably short period of time.

MR. MALCOLM: In other words, it would take a long period of time for it to rehydrate?

DR. WEBER: Yes, it would. And, probably would require higher water pressures and temperatures to permit this.

DR. GREEN: Do you think, then, it would be a good idea to run at very high pressures to extract water from serpentines or to reduce the temperature to get the water off?

DR. WEBER: No, not at temperatures above which the reversable reaction took place, much below that.

DR. GREEN: You could get down to much lower temperatures, because you would be working at lower pressures?

DR. WEBER: If you can work at very low temperatures, (because the curve is sloping in this direction), you could get down to much lower temperatures.

DR. GREEN: Do you think these will be applicable to other rock types (minerals)?

DR. WEBER: Yes, there is another paper that I understand will be presented in the published proceedings, which will give all the data for kaolinite, dichite, halloysite, brucite and a few others we looked at. Somewhat more vapor pressure will be generated in the dehydration kiln and it appears from the data that we present that those pressures should be kept as low as possible. You should condense it just as fast as you possibly can.

DR. GLASER: What can you say about the volume effect of dehydration? If you have a large block of serpentine, how does the dehydration proceed, from the surface inwards?

DR. WEBER: Using high pressure DTA we couldn't say very much about the reaction measurements about 15 PSI but Dr. Greenley of Penn State has been studying the dehydration of serpentine, at much lower vapor pressures, going down to a fraction of a millimeter of mercury and he has studied this particular problem. He believes the reaction is the fusion control and that's about all I can say until his material is also published.

REMOVAL OF OXYGEN FROM OXIDES BY FUSED SALT

ELECTROLYSIS IN A VACUUM

Paul G. Herold
H. J. Boving

All metallic aluminum presently is extracted from the relatively pure aluminum oxide by the process of fused salt electrolysis. In this Hall Process, the salt is cryolite and the electrodes are carbon. The materials produced are molten aluminum at the cathode and oxygen at the anode which combines to form carbon monoxide. In this process, about 0.85 pounds of carbon are consumed per pound of aluminum extracted. The carbon is consumed both by the oxygen generated at the anode and by the oxygen in the air since the cell is operated at atmospheric pressure. The cell is operated at 900 to 1000°C., the power necessary for heating the electrolyte being supplied by the D.C. current at 5.5 to 7 volts and 8,000 to 40,000 amperes.

Since it seems reasonable that the rocks on the lunar surface could be some form of metallic oxides or suboxides, it has been deemed feasible to consider them as a source of oxygen for maintenance of life support on the lunar base. One of the methods of extraction to be investigated should apparently be the fused salt electrolysis method. The limiting areas which need to be investigated in order to adapt the method to the lunar enviornment are:

1. Development of a suitable electrolyte.
2. Development of an electrical conductor which will withstand the corrosion of the molten electrolyte.
3. A mechanical design which will allow collection of the gas produced.

The first tests made were conducted using molten cryolite as the electrolyte. Although molten cryolite is very stable at atmospheric pressure, it is easily vaporized at temperatures just below it melting point in a vacuum. At the melting point, cryolite changes to a vapor instantaneously at a pressure of 1 x 10^{-4} Torr. Therefore, it was found necessary to develop an electrolyte composed of more stable materials. Since many authorities have stated that the lunar surface seems to be composed of volcanic rocks, a typical lava composition was tried next. Prestwich* reports the following composition of a lava from Iceland:

Silica, SiO_2	50.75%
Alumina, Al_2O_3	16.53
Iron Oxide, Fe_2O_3	2.10
" " , FeO	7.89
Magnesia, MgO	7.65
Calcium Oxide, CaO	11.96
Soda, Na_2O	2.13
Potash, K_2O	.56
Ignition Loss	.35

This mixture was made from the raw materials silica sand, Alcan low alkali alumina, hematite, ferrous iron oxide, $MgCO_3$, $CaCO_3$, $NaCO_3 \cdot H_2O$. and K_2CO_3. The calculated mixture was ground together and calcined to 800°C in air at atmospheric pressure. This was reground through 65 mesh and placed in an iron crucible. When heated at 1150°C for 100 hours in a vacuum of 5 x 10^{-5} Torr, the material forms a greenish colored glass at first. At the end of about 80 hours the glass starts to crystallize into a solid black mass. X-ray analysis shows this crystalline material to be Pigeonite $(Ca_{0.07}\ Mg_{0.45}\ Fe_{0.48})\ SiO_3$. The type material is from Yumoto, Hakone Volcano, Japan. Chemical analyses of the original calcined material, the molten material and the same material after 100 hours of heating in vacuum are as follows:

*Geology by Joseph Prestwich, p.37, Clarendon Press, Oxford.

	Calcined Material	Fused Material	Material held 100 hours in vacuum
Silica, SiO_2	52.18	52.26	48.04
Alumina, Al_2O_3	17.93	17.70	14.14
Iron Oxide as Fe_2O_3	9.43	9.85	22.32
Calcium Oxide, CaO	12.24	11.97	11.92
Magnesia, MgO	3.63	3.25	3.43
Potash, K_2O	.39	.41	.20
Soda, Na_2O	3.53	3.82	.50

As expected, there is very little difference between the calcined material and the fused material. After being held for 100 hours in vacuum at 1150°C, the material has decreased considerably in alkalies, as these oxides are quite volatile. The iron oxide content has increased which may be due to solution of the iron crucible into the melt. The crucible seemed to be intact under these conditions even though similar heating in air would have caused complete destruction within a few hours. The reason for this is that an iron crucible at atmospheric pressure oxidizes rapidly and the iron oxide thus formed is very soluble in the melt.

In the next experiments, the fused volcanic glass was held in an iron crucible and a soft iron electrode 3/8" in diameter was suspended ¼" above the bottom of the crucible. A potential of 5 volts D.C. was applied between the electrodes, and the amperage measured and plotted against temp. See Figure 1.

Various experimental conditions were used as summarized below:

Experiment	Volts, D.C.	Time at 1150°C.	% Weight Loss	Max. Current	Pressure
A	5	2 hours		100 mA	5×10^{-5} Torr
B	7.5	2 hr. 50'	.7	50 mA	"
C	10	3 " 30'	.81	2 A	"
D	5	5 " 45'	1.72	500 mA	"
E	0	5 "	1.17		"
F	5	100 "		8 A	"

Page 116 shows a polished section of the slag resulting from Experiment D. The dendrites are metallic iron while the gray crystals are $MgO \cdot SiO_2$. The iron is seen to be collecting on the wall of the iron crucible at the bottom of the picture. The crucible wall was the negative electrode of the cell.

Two experiments were made on the same volcanic glass composition except that the Fe_2O_3 and FeO were removed. This was done in order to determine the affect on transfer of current in the cell. Following is a summary of conditions:

Experiment	Volts,D.C.	Time	Temp.	%Weight Loss	Max. Current	Pressure.
G	5	100 Hr	1150°	20.0	150 μA	2×10^{-5} Torr
H	5	50 "	1210°	42.0	6 A	"

Experiment G did not become fused at 1150°C, but the current flow resulted from condensation of iron on the surface of the material. Experiment H resulted in a green glass containing many small particles of iron. Apparently iron is being detached from the anode and carried to the cathode.

No measure of gas coming from the anode could be made as the evolution is too slow to show up as an increase in pressure in the system. It is planned to obtain a Residual Gas Analyzer so as to be able to measure and identify the gases being evolved. The weight loss shows that something is happening in the system, however, it is not accurate because of the experimental conditions. A more refined system of weight loss needs to be used. This was impossible at the time because of lack of funds.

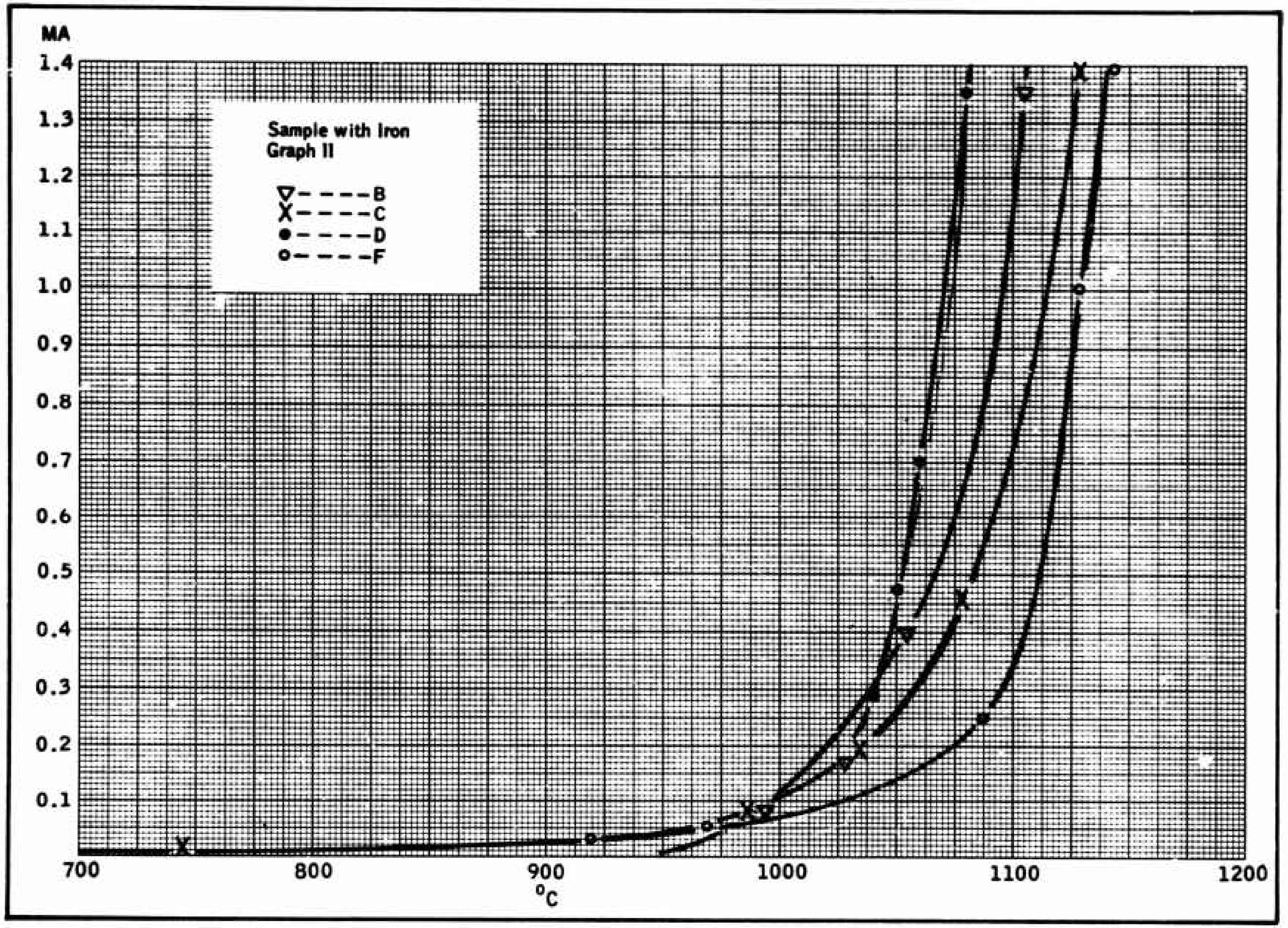
MA
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Sample with Iron
Graph II
▽----B
X----C
●----D
o----F
700
800
900
1000
1100
1200
°C

Figure 1.

Figure 2. Experiment D. 90 Magnification

STABILITY - METASTABILITY RELATIONSHIPS OF HYDROUS MINERALS AND THEIR IMPORTANCE IN DESIGNING FACILITIES FOR THE EXTRACTION OF WATER FROM LUNAR ROCKS AND MINERALS

R. Roy
J. N. Weber

Abstract

Reaction curves defining the pressure-temperature values for the dehydration of hydrous minerals are generally available for water pressures exceeding 5000 psi. To design and construct water extraction facilities on the moon, however, data concerning the decomposition of hydrated minerals at lower water vapor pressures are essential. Extrapolation of published reaction curves to lower pressures will not provide the necessary information for many minerals containing hydroxyl groups since recent studies have shown that certain minerals may persist metastably at temperatures much above the values predicted for decomposition. Pressure-temperature points for the reaction: hydrated mineral → solid product + water, have been determined by means of differential thermal analysis employing the Herold-Planje thermocouple arrangement sealed in a pressure vessel in which water pressure can be controlled and measured. Simple structures such as brucite dehydrate readily at temperatures approximating those predicted by extrapolation

of high pressure stability fields. Complex silicates such as serpentine, kaolinite, dickite and halloysite, however, metastably retain their hydroxyl groups in the stability field of product + water until relatively high temperatures are attained. Dehydration temperatures for the latter group of minerals increase with increasing P_{H_2O} until a point at which the catalytic effect of water facilitates structural reorganization and dehydration. Above this pressure, about 1000 psi in the case of kaolinite, decomposition temperatures decrease with increasing pressure up to 10,000 psi. Dehydration curves from 15 to 10,000 psi for a variety of minerals are presented.

Proposed water extraction facilities for a lunar base involve kilns in which hydrous minerals such as serpentine are heated to temperatures at which decomposition of the structure and the liberation of water takes place. The selection of optimum operating temperatures and pressures of water vapor is essential for efficient and economical exploitation of possible natural resources on the moon.

Stability curves for a number of common minerals containing water are shown in figure 1. These curves, defining the water pressure and temperature conditions at which decomposition occurs have been determined at relatively high pressures, usually in the range 100 to 10,000 bars. Plotted as the logarithm of the water pressure and the reciprocal of the absolute temperature, the pressure-temperature dehydration curves are linear, and extrapolation to lower water pressures such as those possible in dehydration kilns designed for the moon would appear to define the minimum temperatures required for dehydroxylation.

Thermal experiments at atmospheric pressure, however, have shown that for many minerals, temperatures much above the temperature at which a given mineral is stable, are required to effect dehydration. The stability curve for kaolinite, for example, is shown as curve I in figure 2. Determined at pressures above 1000 psi by Roy and Osborn (1954), this curve indicates that dehydroxylation of kaolinite should take place above about 400° C over a wide range of water pressure. Differential thermal analysis data (Curve II, figure 2) presented by Ellis and Mortland (1962), however, indicate that temperatures in the range 475 to 575° C are necessary to liberate hydroxyl

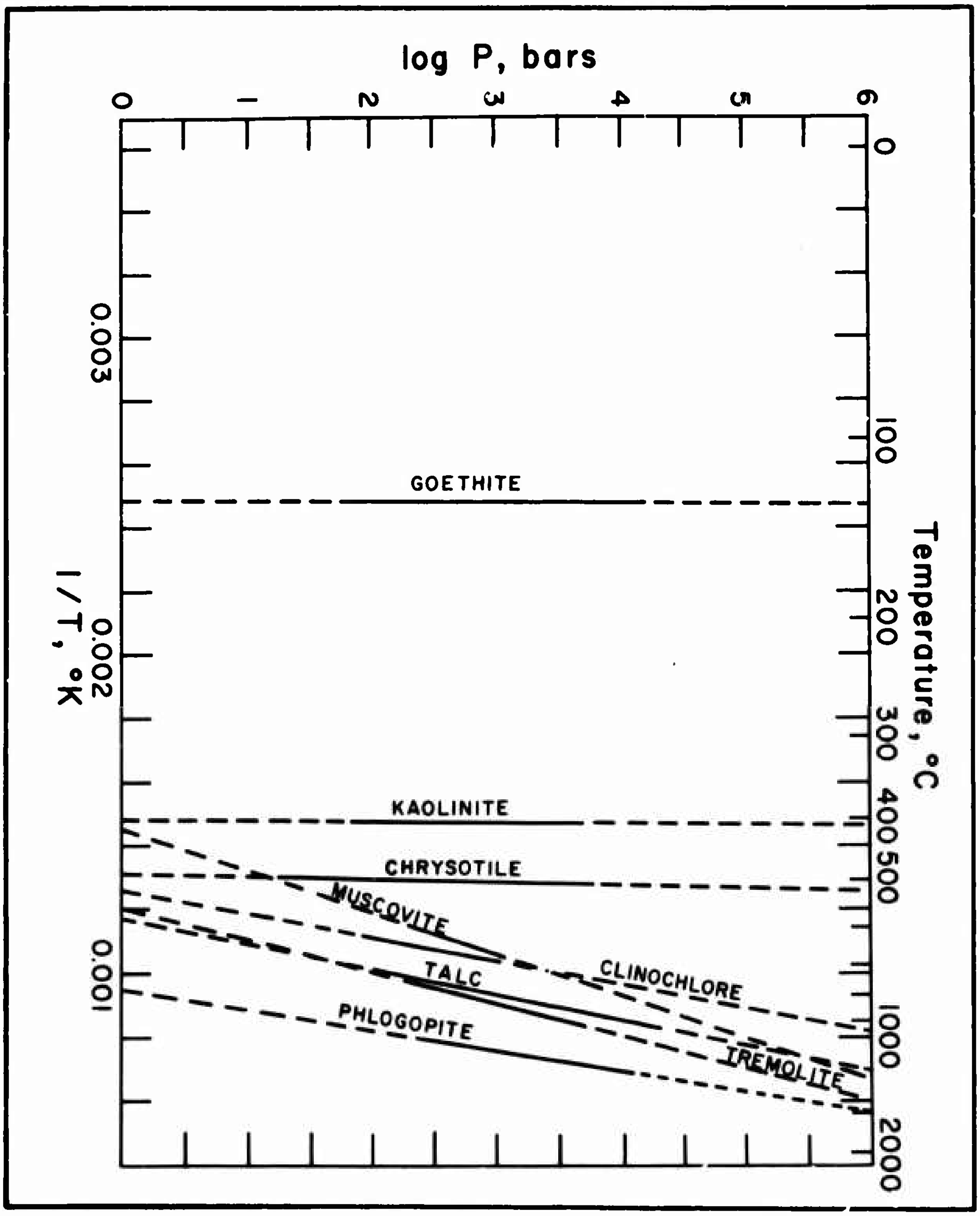

Figure 1. High pressure stability curves for a variety of hydrous minerals.

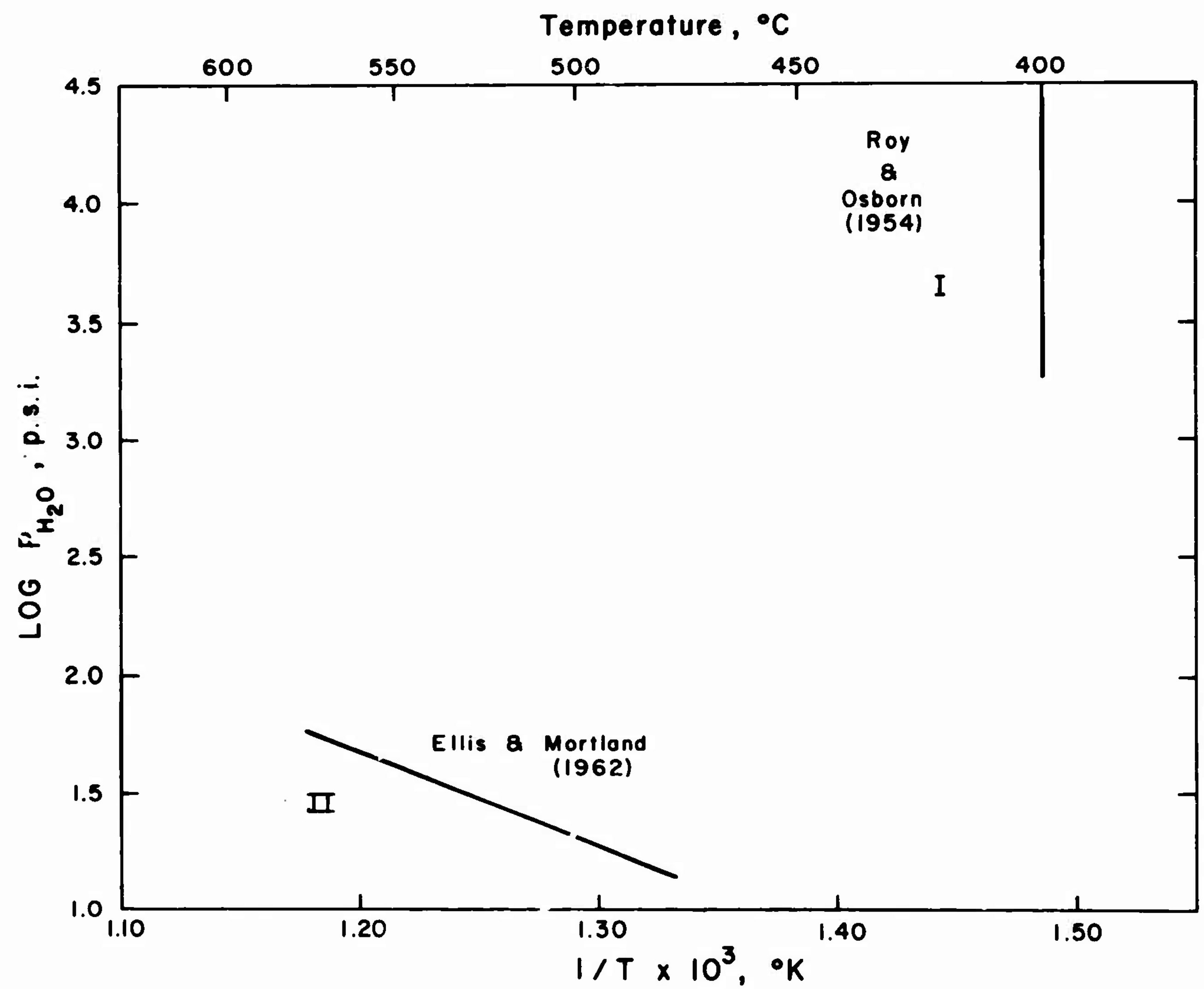

Figure 2. Comparison of pressure-temperature data obtained at high pressures (Ray and Osborn 1954) with data obtained at relatively low pressures (Ellis and Mortland 1962) for kaolinite. Decomposition of this mineral was observed at temperatures to the left of each curve.

water at pressures of water vapor in the vicinity of 15 psi.

Stability-metastability relationships are illustrated in figure 3. Curve I represents experimentally determined pressure-temperature points at which phases A_s, B and water can coexist. At point M, A_s is a stable hydrous mineral phase. On raising the temperature while maintaining the same water pressure, from point M to O to N, decomposition begins at point O. At temperatures greater than that at point O, the dehydration product B and water constitute the stable phase assemblage. If the temperature of A_s is increased at a lower pressure of H_2O, for example from S to P, Q, and T, it might be expected that dehydration of A_s would take place at point P, the intersection of the temperature-pressure traverse (S-T) with curve I extrapolated to lower pressures. As shown by the data presented in this paper, decomposition of many hydrous minerals with concurrent release or evolution of water does not take place at the temperature where the mineral ceases to be a stable phase. Such minerals retain their identity and persist metastably in the region indicated by A_m. At a much higher temperature, Q, the metastable phase decomposes to yield a solid dehydration product C and water. The pressure-temperature points for dehydroxylation of the metastable phase are represented by Curve II. At some pressure near the upper limit of curve II, the catalytic effect of water facilitates reorganization of the mineral structure. It should be noted that the solid decomposition product (B) obtained by dehydration of the stable phase of a given mineral need not be identical to the solid decomposition product (C) formed at lower water pressures.

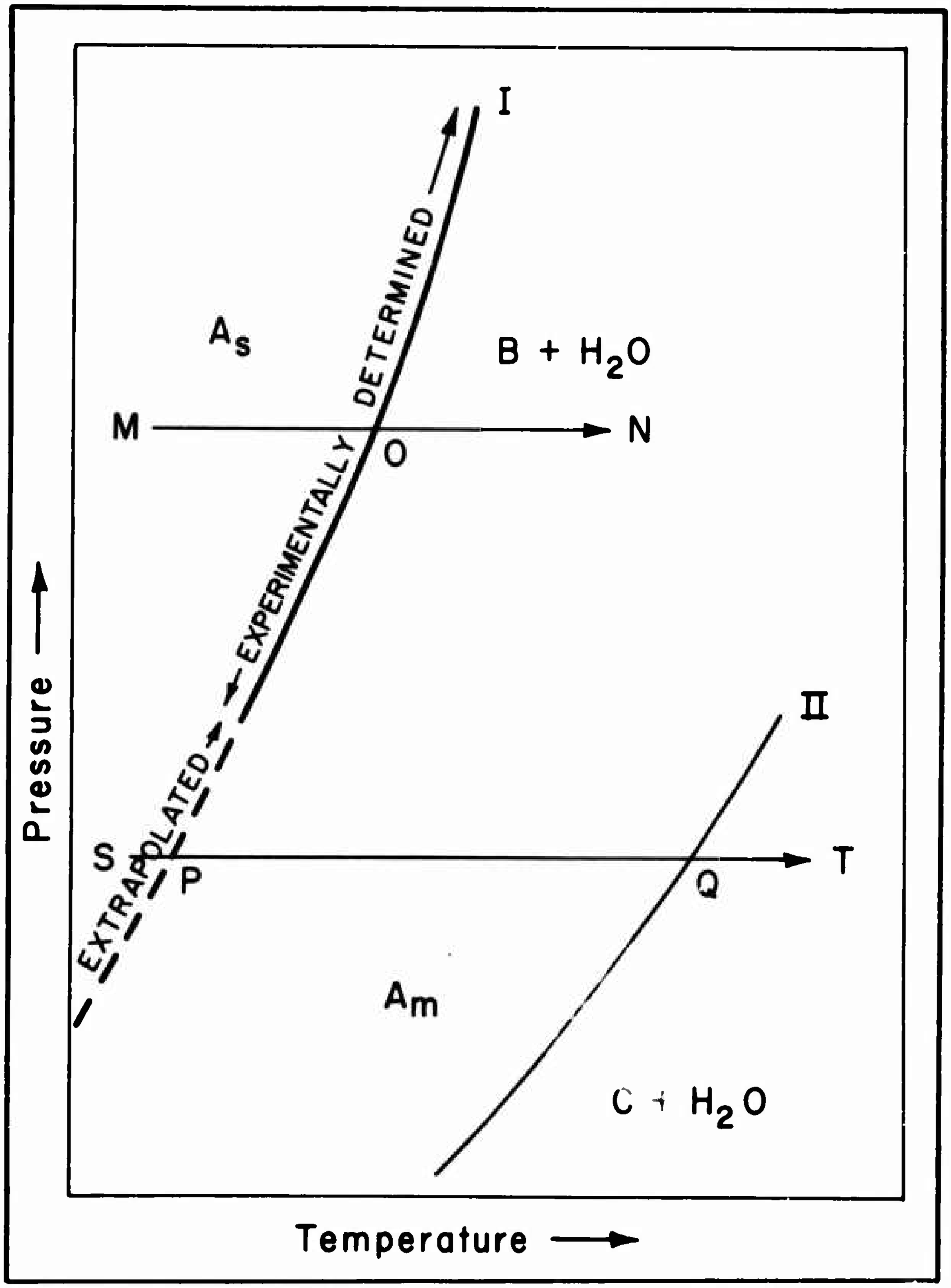

Figure 3. Hypothetical pressure-temperature dehydration curves to illustrate decomposition of the stable phase (Curve I) and metastable phase (Curve II) of a given mineral.

Pressure-temperature dehydration curves obtained by high pressure differential thermal analysis are shown in figures 4. 5, and 6 for kaolinite, dickite and halloysite respectively. The dehydration temperatures are much higher than the maximum temperature at which these phases are stable. From 15 psi to about 1000 psi, dehydroxylation temperatures increase with increasing water pressure, but above 1000 psi lower temperatures are required for decomposition.

Dehydration curves for serpentine, a mineral whose existence on the moon is probable, have been presented in the adjoining paper (Weber, Roy and Greer). Serpentine, kaolinite, dickite, and halloysite possess rather complex silicate structures. For comparison, brucite (magnesium hydroxide) has been studied under the same experimental conditions. Pressure-temperature poin[illegible] the dehydration of this mineral are shown in figure 7; much less scatter is immediately evident. Comparison of this curve (marked Weber and Roy) with other published data (figure 8) obtained by a variety of experimental techniques indicates that decomposition under conditions applicable to lunar water extraction devices takes place at temperatures not much above the maximum temperature at which coarsely crystalline, unstrained brucite is stable.

This research was sponsored by the Air Force Cambridge Research Laboratories, Office of Aerospace Research, under contract AF 19(628)-2773.

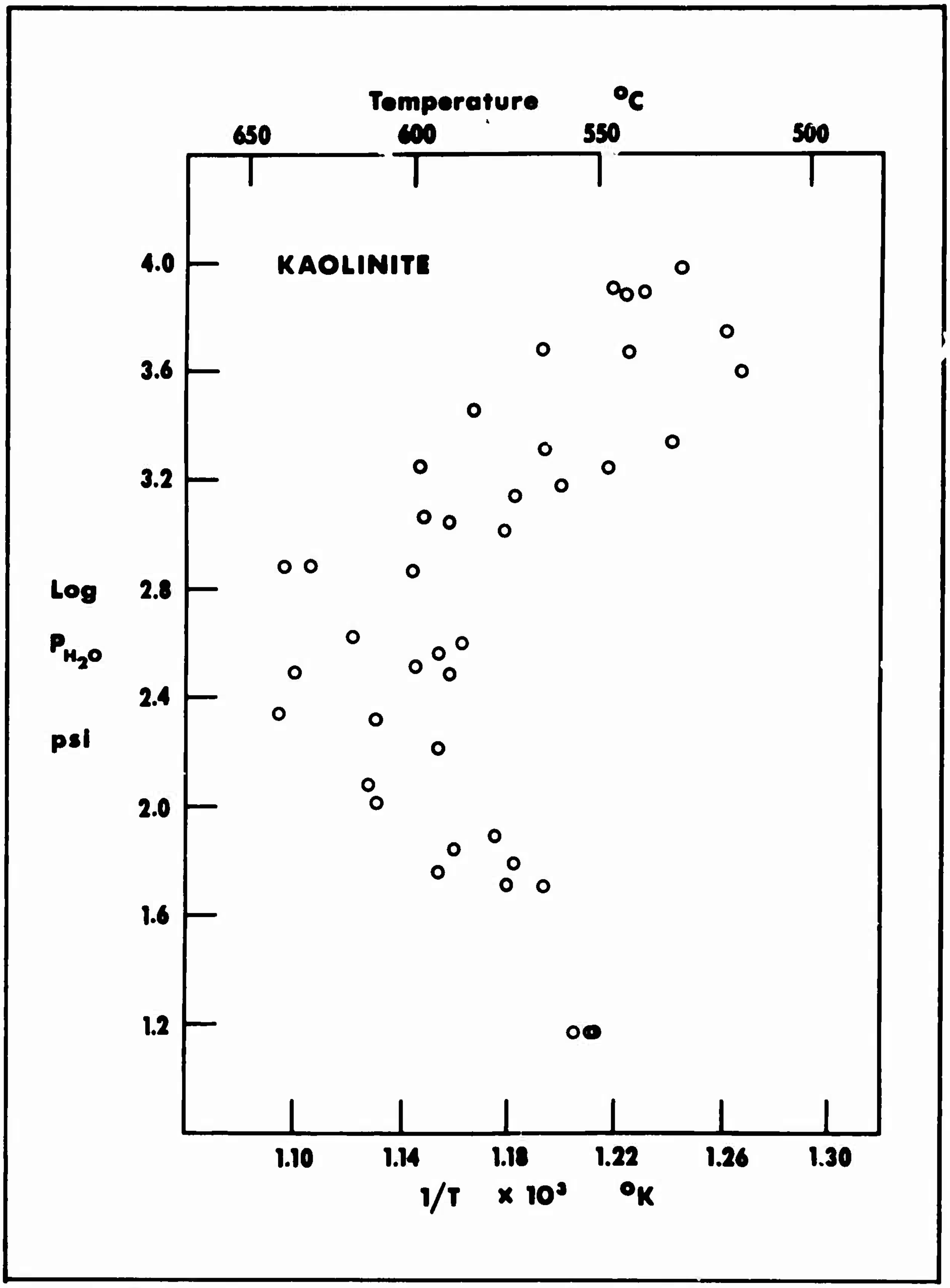

Figure 4. High pressure differential thermal analysis data for the dehydration of kaolinite.

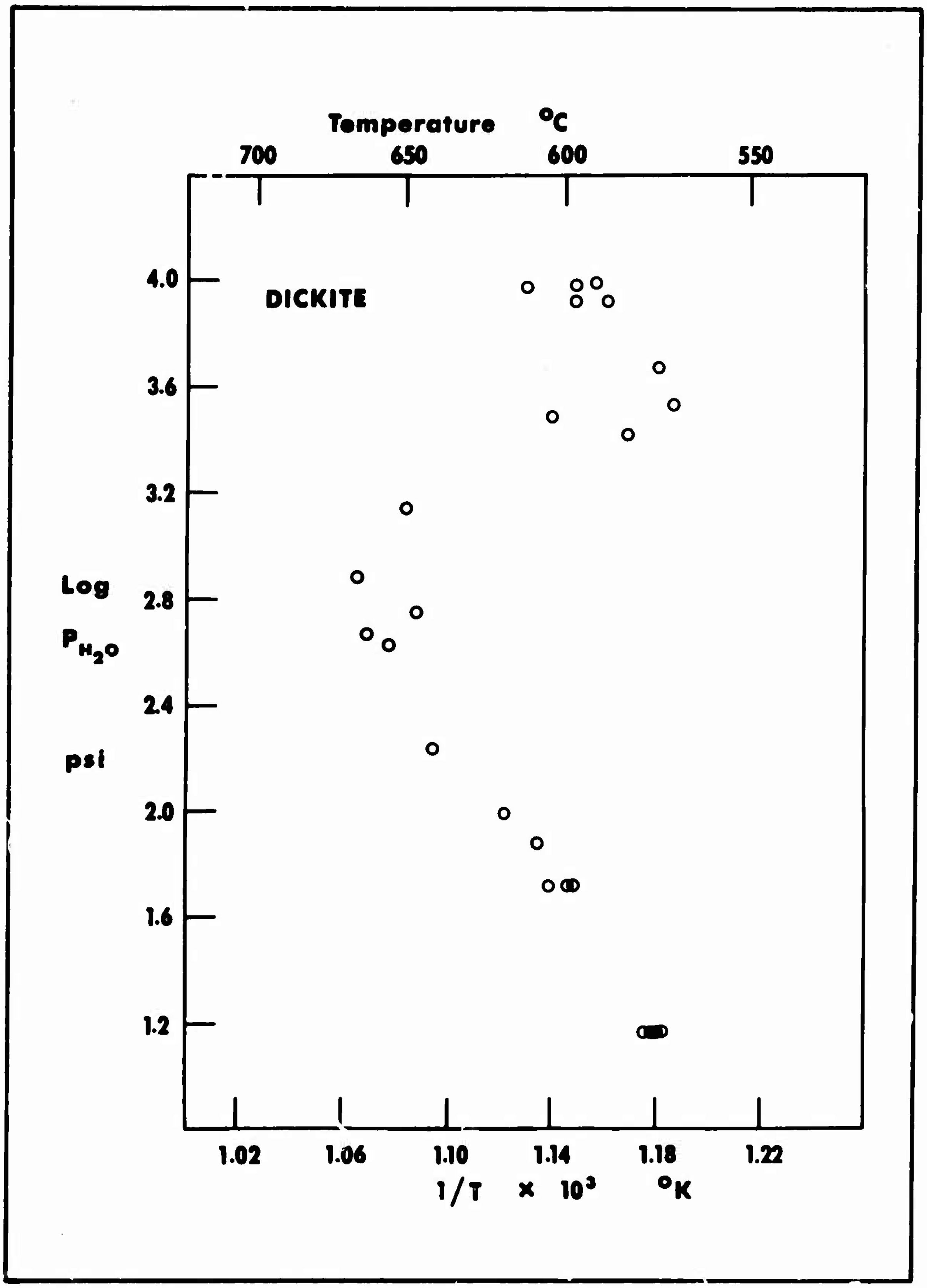

Figure 5. High pressure differential thermal analysis data for the dehydration of dickite.

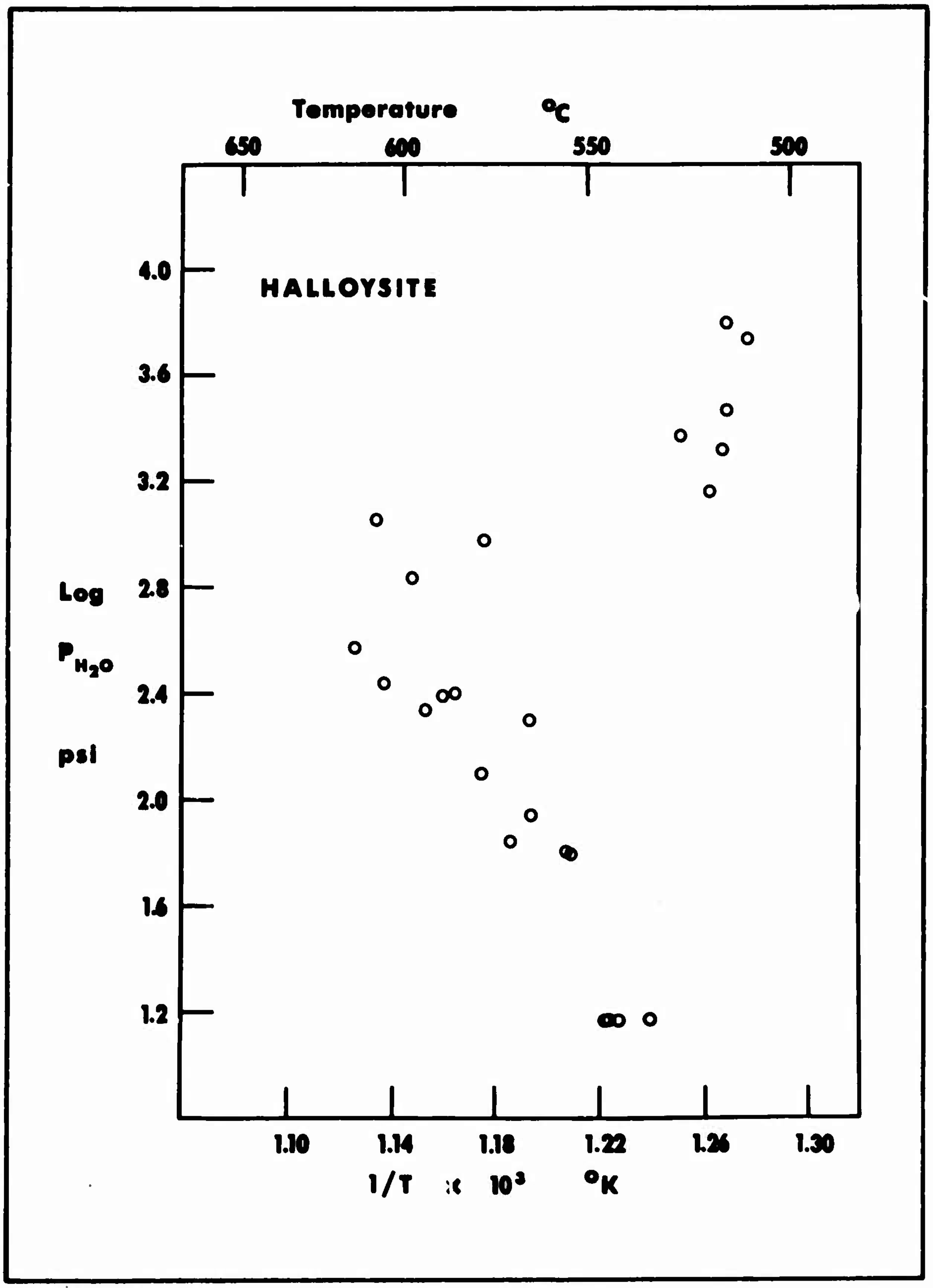

Figure 6. High pressure differential thermal analysis data for the dehydration of halloysite.

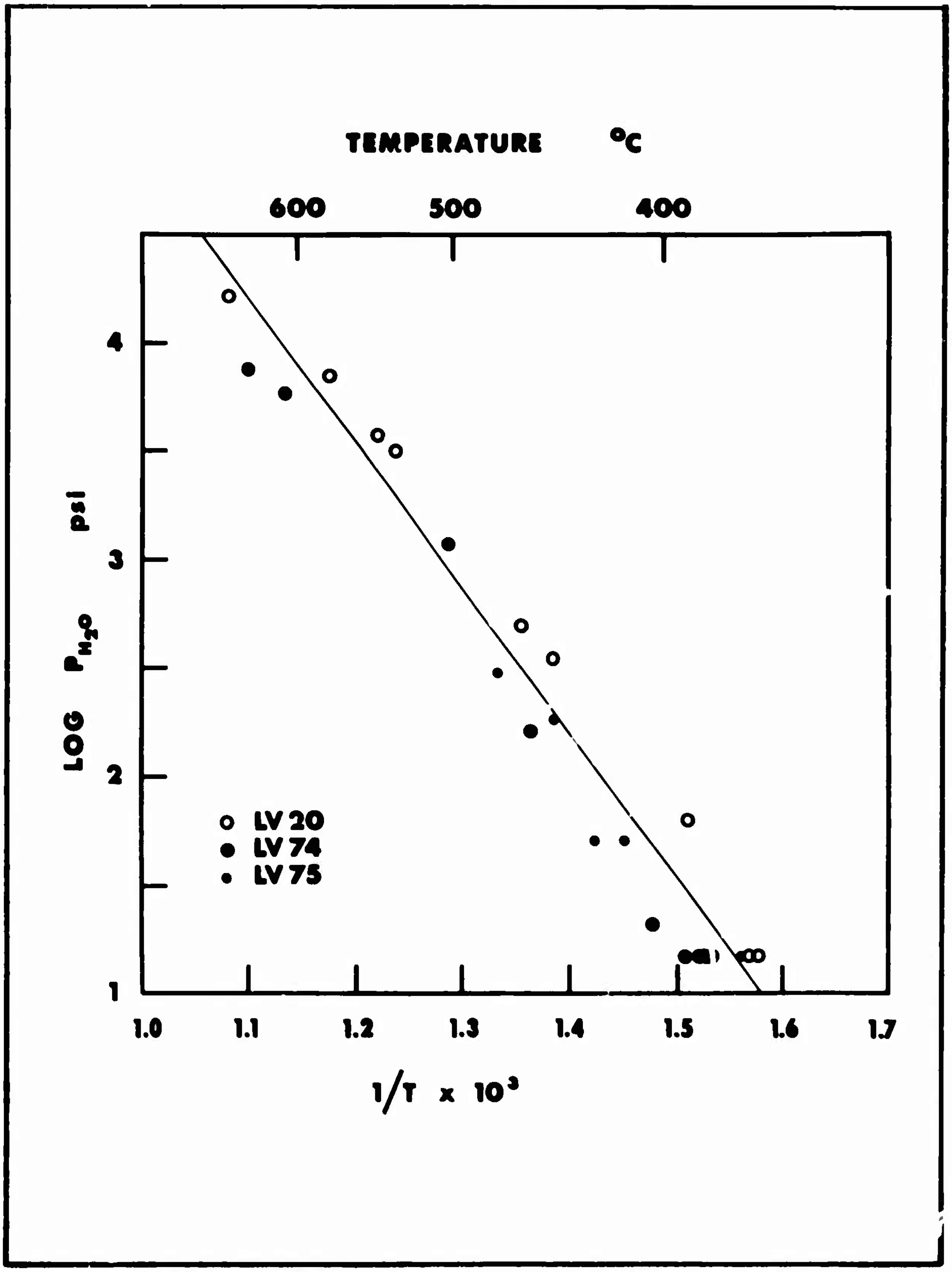

Figure 7. High pressure differential thermal analysis data for the dehydration of brucite.

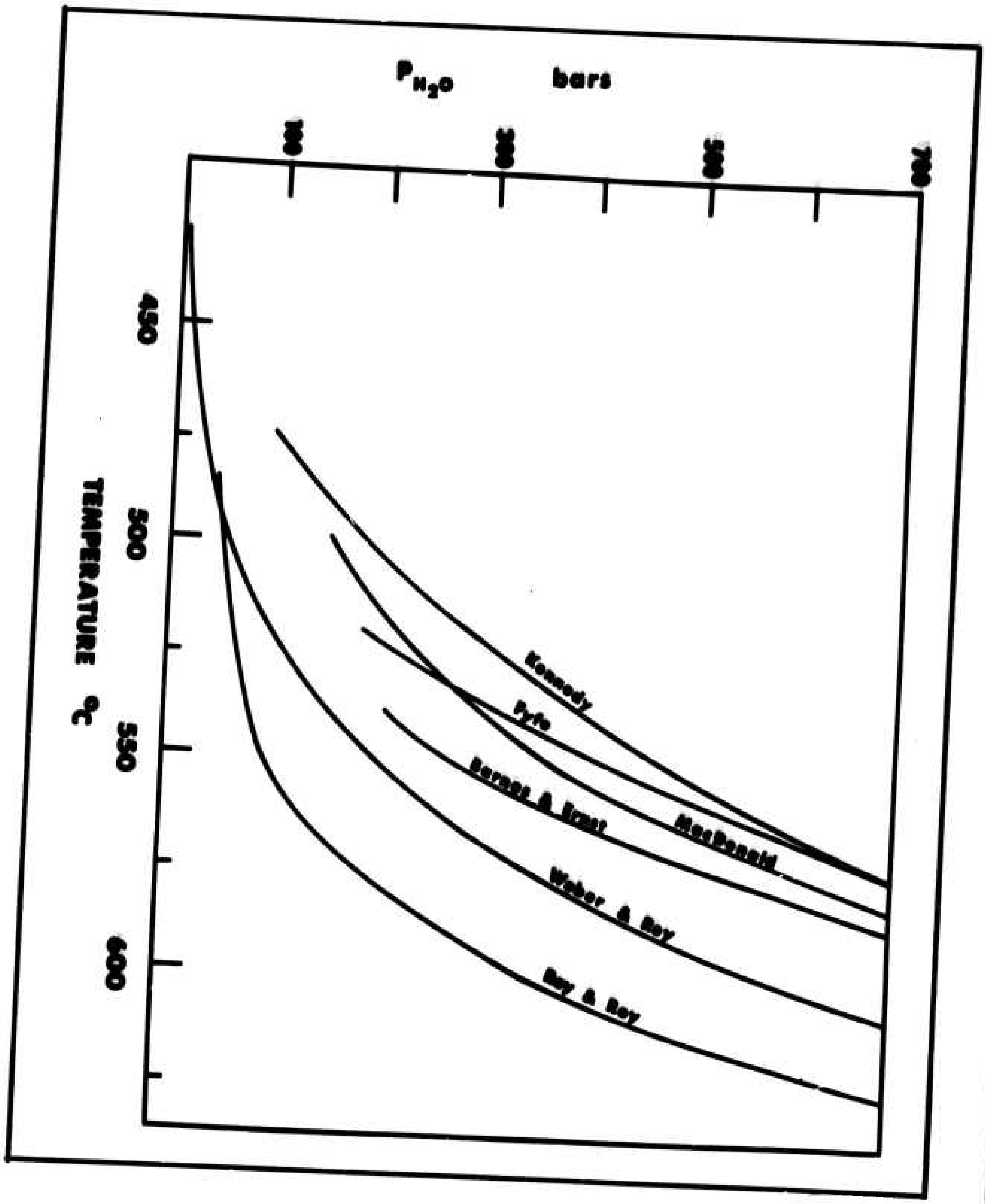

Figure 8. Comparison of the dehydration curve for brucite shown in figure 7 (marked Weber and Roy in this figure) with similar curves published by Kennedy (1956), Fyfe (1958), MacDonald (1955), Barnes and Ernst (1936) and Roy (1957).

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ARNOLD ENGINEERING DEVELOPMENT CENTER LUBRICATION PROGRAMS

John D. Peters

Until the inception of space flight, lubrication was well within the state-of-the-art. However, as higher and higher altitudes were reached there was an increasing awareness of special material and lubrication requirements. One of the better known problems was the failure of generators whose carbon brushes began to pulverize because of moisture evacuating from the carbon structure.

The space age introduced a new era in the field of lubrication. In addition to the normal demands imposed by load, speed and vibration, lubricants were required to withstand the space environmental extremes of temperature, vacuum and radiation, without appreciable loss of lubricity. Development of lubricants and lubrication techniques is essential to the successful operation of aerospace systems and facilities.

In the normal design of machines, lubrication is a secondary consideration. However, for the operation of mechanisms in the space environment, lubrication must be considered concurrent with the design of the system. In those instances where existing equipment can be used in the space environment, it is often necessary to design a complete lubrication system to ensure maintenance-free operation.

Ground space facility lubrication problems are generally those associated with the vehicle handling system. Large space chamber equipment can include overhead cranes operating on suspended rails, electric motors, hand hoists, hinged doors and rotatable vehicle mounts. Figure 1 is a conceptual space vehicle on a rotatable mount in the Arnold Center's Mark I Space Chamber.

In space, lubrication problems are those concerned with the moving components of the vehicle itself. Typical space vehicle moving mechanisms are micro switches, rotatable solar paddles, extendable antennae, gyros and vectoring stabilization rockets. Figure 2 shows the movable temperature control louvers of NASA's Orbiting Geophysical Observatory.

Programs of recent and continuing interest at Arnold Center are the investigation of lubrication by solid, thin sacrificial films and by transferring, replenishable solids. The latter method involves the rubbing of a solid lubricant against moving parts thus causing the lubricant to be continuously transferred to the contacting load-bearing surfaces. The former method is a once only application of a thin adherent lubricant film to each of the contacting surfaces.

Research on thin films was accomplished by the General Electric Company under contract to the United States Air Force, Arnold Engineering Development Center. Emphasis was placed on the lubrication of heavily loaded, low velocity bearings and gears. Figure 3 is an artist's sketch of the Arnold Center 7-ft diameter by 12-ft long Aerospace Research Chamber and Figure 4 shows the test apparatus

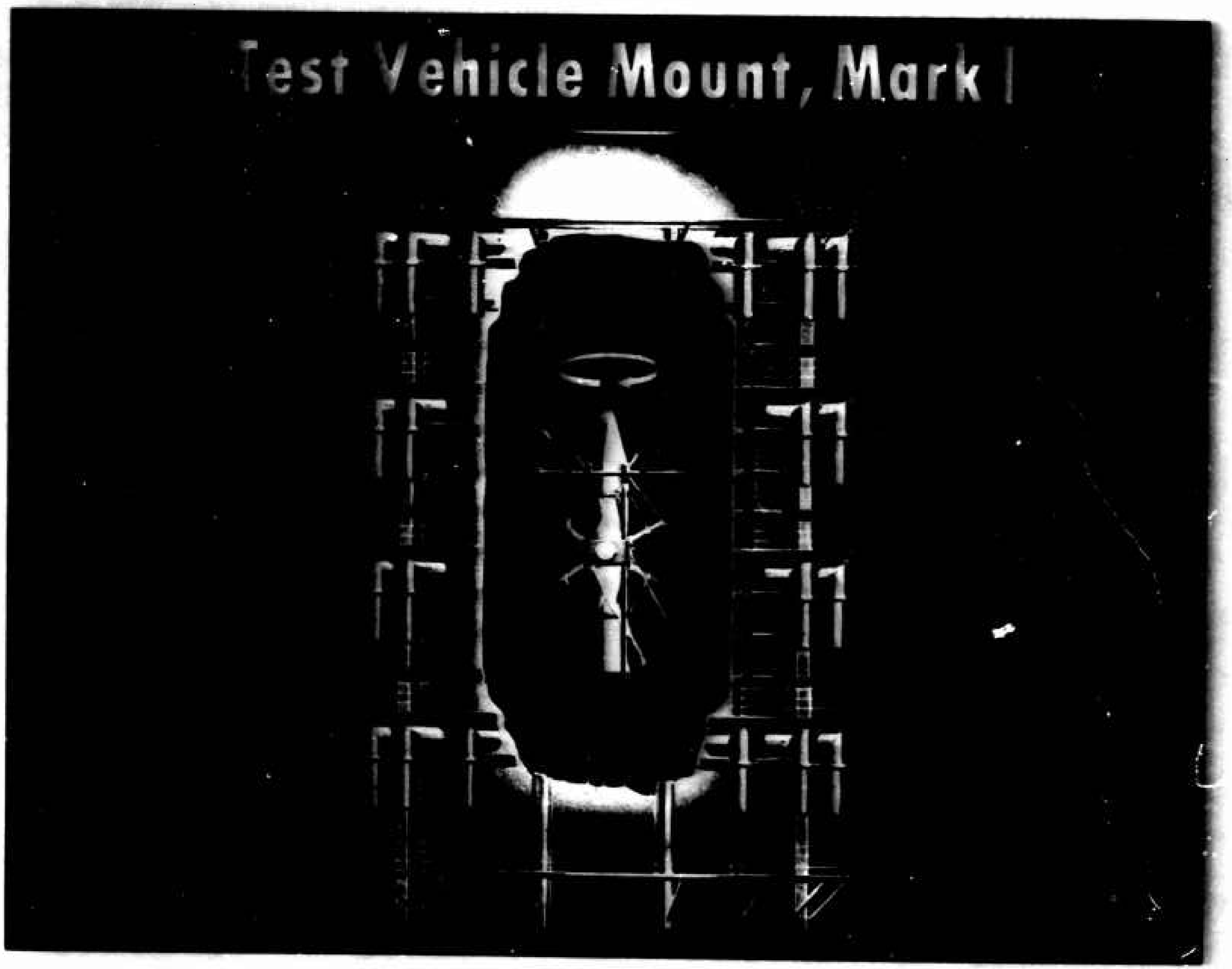


Fig. 1 - Test Vehicle Mount, Mark I

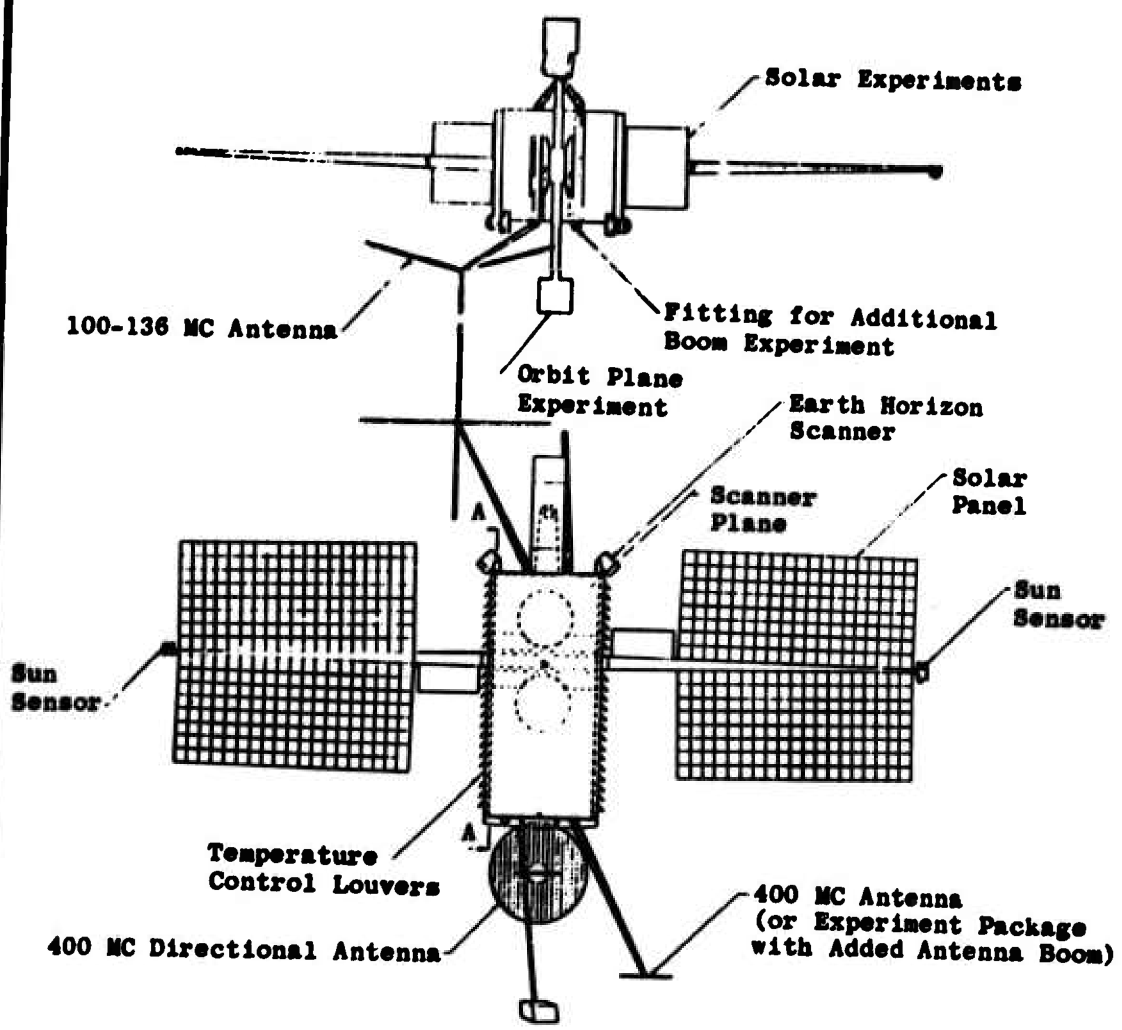


Fig. 2 - Externa' Arrangement of AGO Vehicle Configuration

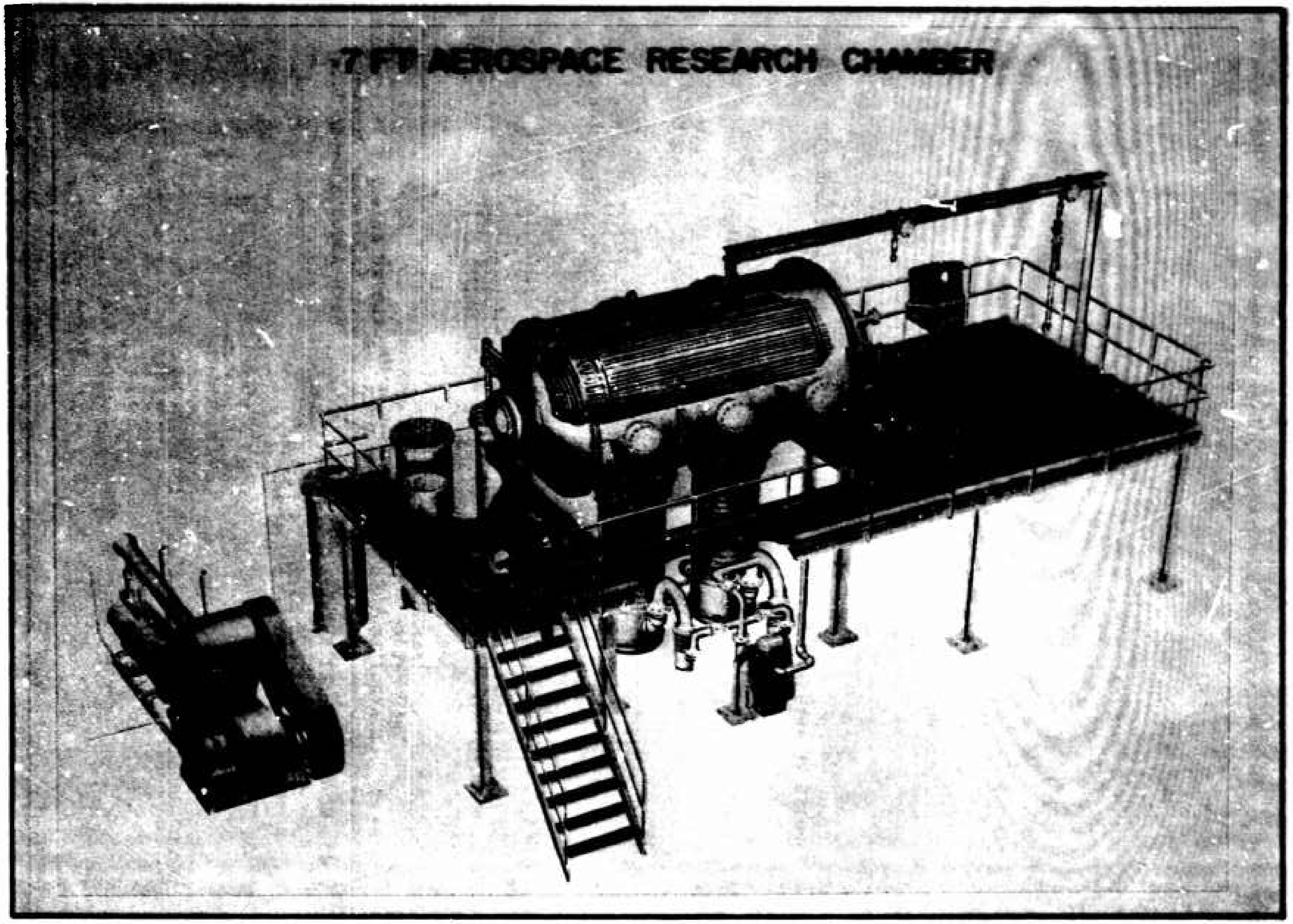


Fig. 3 - Aerospace Research Chamber (7 Ft)

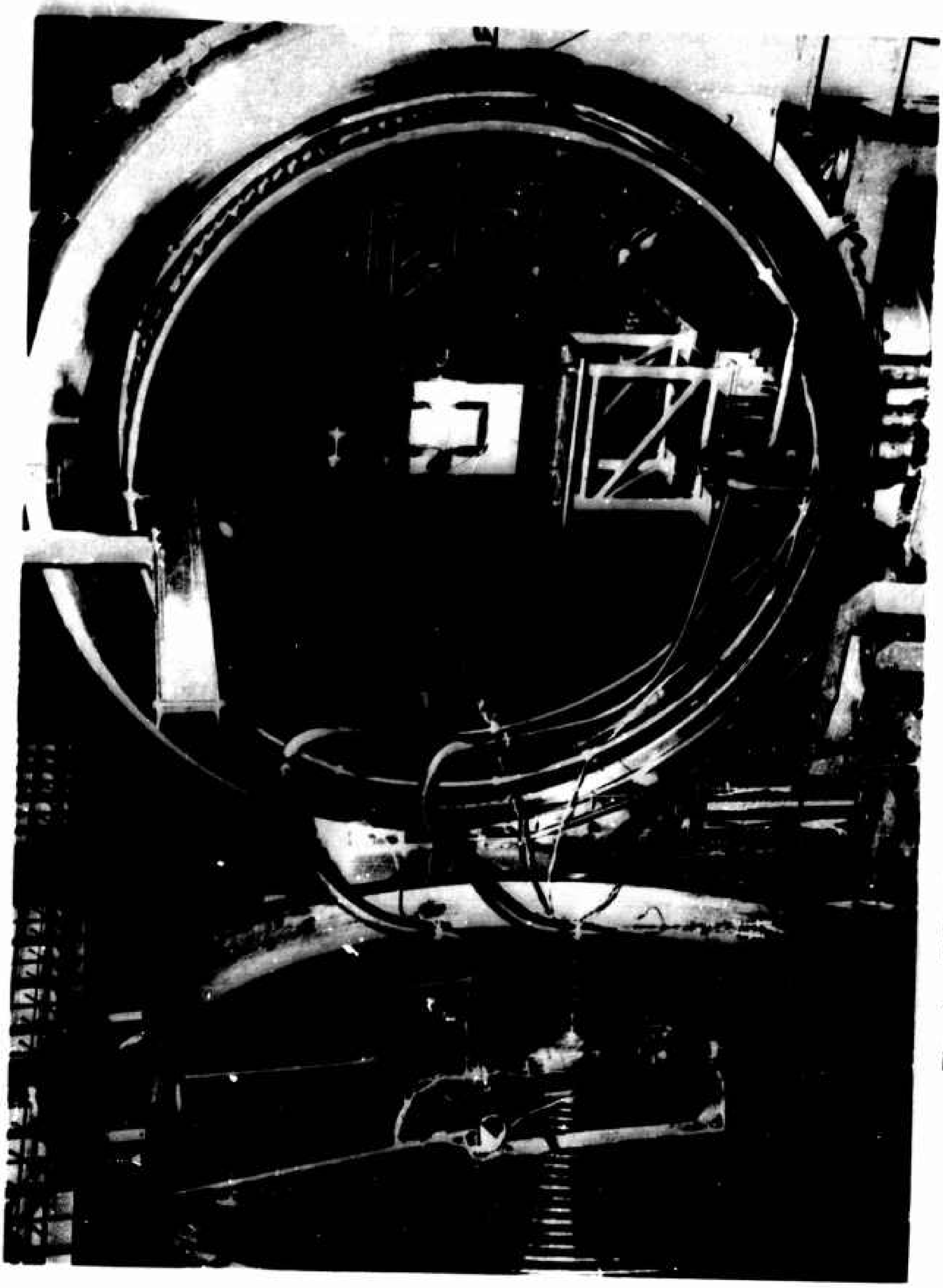


Fig. 4 - 7 Ft. Aerospace Chamber with Bearing Tester in Foreground and Four Square Gear Tester in Background

installed. Figure 5 shows a silver plated cylindrical bearing and Figure 6 is an example of gears which were tested. Figure 7 is a table of test results of bearings run in vacuum.

Initial research by the Westinghouse Electric Corporation under contract to the United States Air Force, Arnold Engineering Development Center, was concerned with adapting bearings and gears for use in the space environment. Solid lubricants and replenishing lubrication systems were developed. Hertz stresses for gears varied from 90,000 to 120,000 psi and bearing stresses varied from 155,000 to 200,000 psi. Bearing starts were made at -320°F and ran for extended periods at temperatures from -160°F to +300°F.

Many composites and lubricating compounds were considered. Figure 8 is an example of the wear and friction properties of the screened materials. The most successful materials were composites of teflon, copper and tungsten di-selenide and teflon, silver and tungsten di-selenide. The composite structure can be seen in Figure 9. A typical bearing is shown in Figure 10. Figure 11 shows a gear pinion and idler and Figure 12 shows wear of a pinion which resulted in test termination.

You can appreciate that our programs have been primarily for applied research.

We have just completed another test program where gears were tested under extremely heavy loads. Loads were such that at half load, vacuum greases with solid additives (MoS_2) were unable to withstand the heavy stresses and the oils and additives were squeezed out so that pronounced gear tooth wear occurred. The greases were removed and replaced by solid lubricants and the load was doubled. Testing continued successfully for a period of 100 hours.

If you consider a lunar vehicle such as shown in Figure 13, notice the inner wheels. The use of a solid replenishable lubrication system seems a reasonable solution to the lubrication problem where abrasive dusts may be encountered. As you notice this is a lunar vehicle concept of the Lockheed Missile and Space Company.

The extremes of temperature, vacuum and radiation which can simultaneously prevail in the hostile environment of space impose serious problems when one considers the requirement of maintenance-free operation of a myriad of mechanisms. To satisfy lubrication requirements there must be a spectrum development of lubricants and application techniques. Fortunately it will not be necessary to get out into space to solve these problems since we now have space chambers to provide the simulated environment.

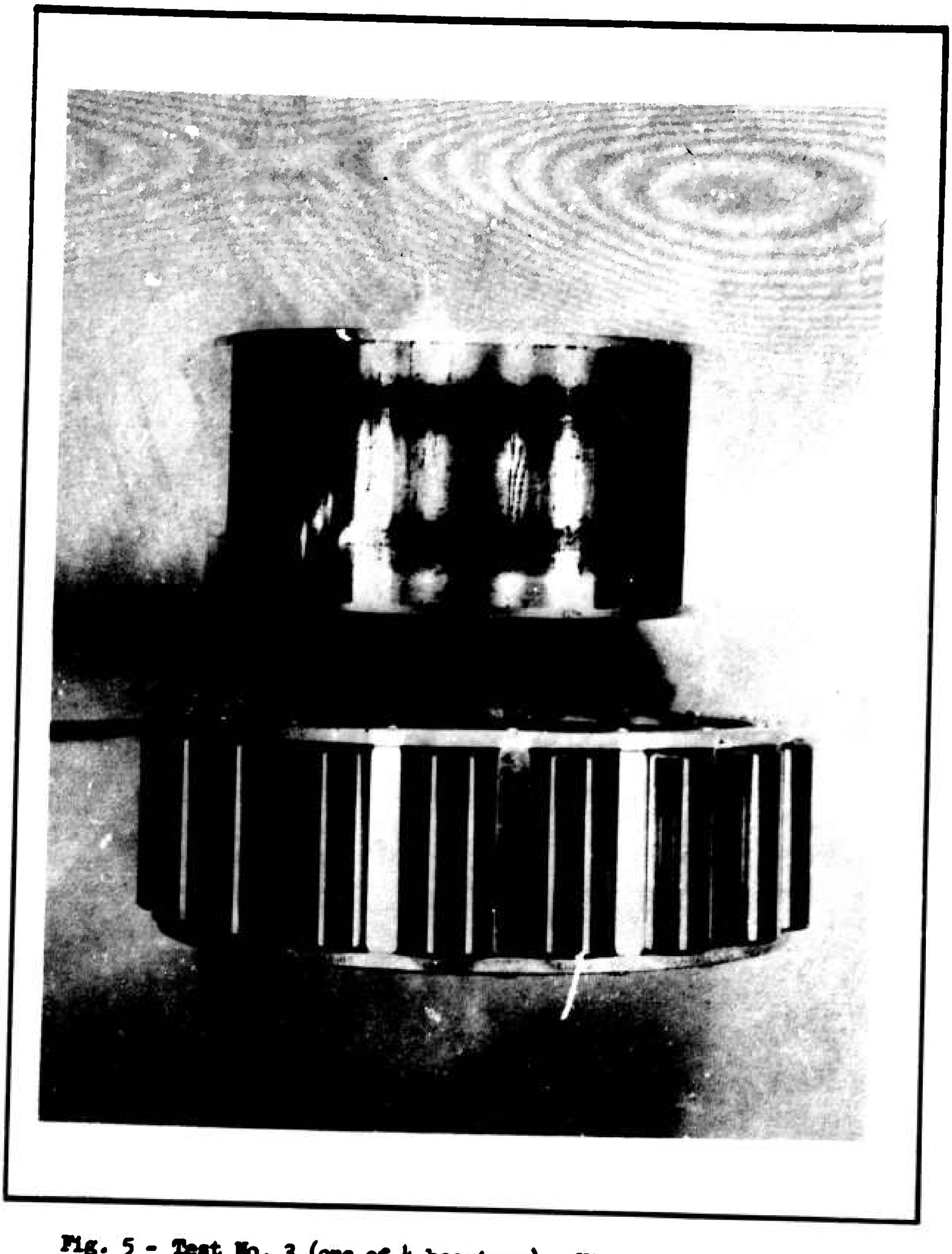


Fig. 5 - Test No. 3 (one of 4 bearings) - View of Ag plated inner race and roller-cage assembly from cylindrical bearing - coating intact and polished

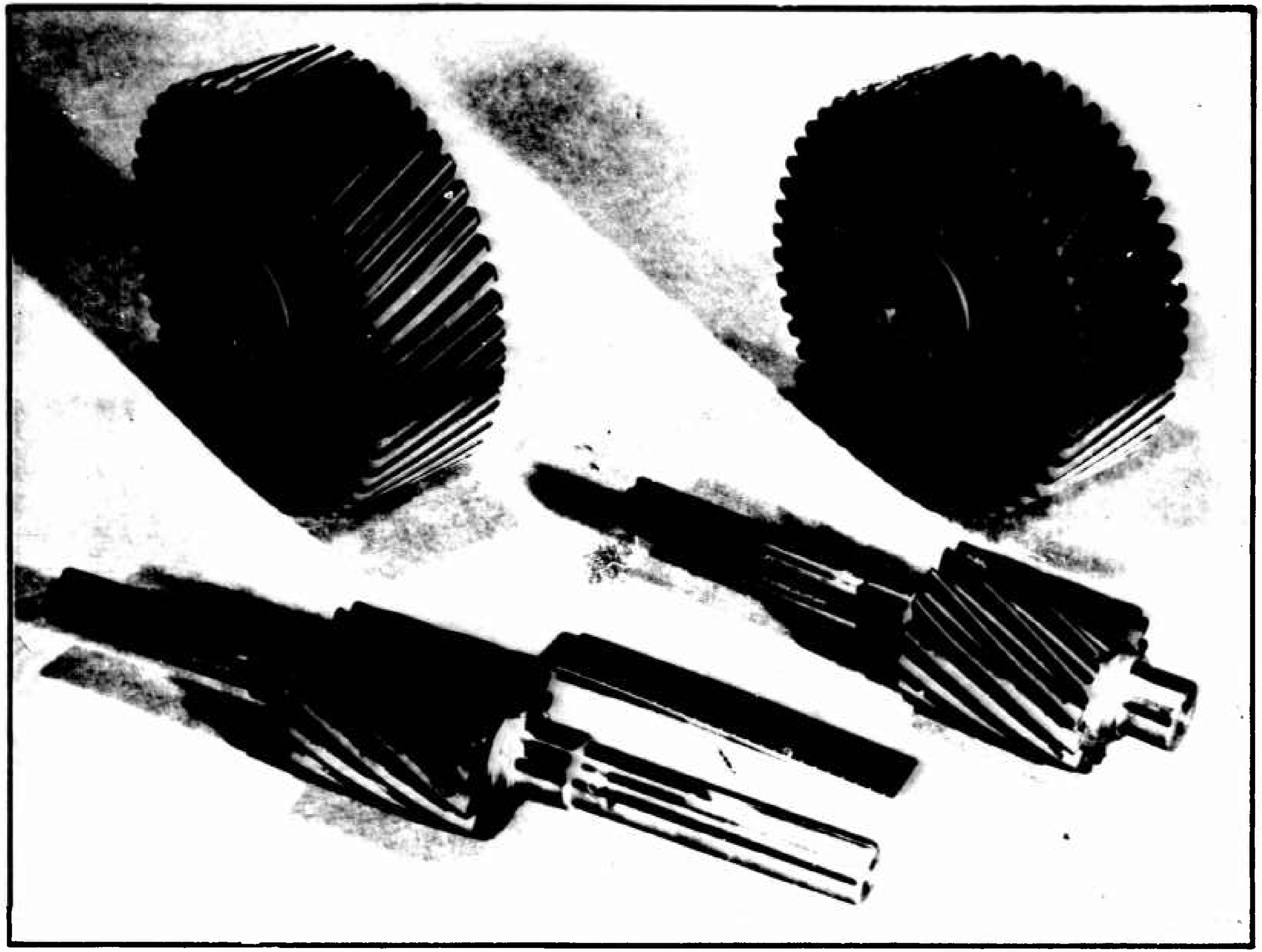


Fig. 6 - Gear Tests - Nos. 1 and 2 - the light areas on the tooth surfaces adjacent to the gear faces indicate depletion of lubricant (Lub. MoS_2 + Epoxy Binder)

TABLE 1

ATL LARGE SCALE BEARING (100 MM) TEST RESULTS

TEST NO.	BEARING TYPE (100 MM)	NO. OF BRGS.	RADIAL LOAD (lb/brg) P_1	RADIAL LOAD (lb/brg) P_2	BEARING STATIC LOAD CAPACITY (Co) lbs.	Co/P[(1)] RATIO Co/P_1	Co/P[(1)] RATIO Co/P_2	LUBRICANT[(2)]	SPEED (RPM)	TOTAL CYCLES	TEST DURATION IN VAC. (HRS.)
	Bearings										
1	SKF 2220CY Spherical EB 5220B Cylindrical	2 2	[illegible] 5,600		56,000 71,000	10.0 12.7		MoS_2 + Epoxy Binder	10	14,101	26.6
2	SKF 2220CY Spherical EB 5220B Cylindrical	2 2	4,000 4,000		56,000 71,000	14.0 17.7		23 Kt Gold	8	1,938	4.4
3	EB 5220B Cylindrical	4	5,100		71,000	14.0		Silver	8	6,239	12.5
4	EB 5220B Cylindrical	4	5,100	7,100	71,000	14.0	10.0	MoS_2 + Graphite + Silicate Binder	8	62,640 + 46,859 109,499	130.0 + 100.0 230.0
5	SKF 2220CY Spherical EB 5220B Cylindrical	2 2	4,000 4,000		56,000 71,000	14.0 17.7		MoS_2 + Glass	8	24,765	53.3
6	220A Ball Bearings	4	2,850		28,500	10.0		Low vapor[(3)] petroleum distillate grease (Apiezon L)	8	36,302	80.0
7	SKF 2220CY Spherical EB 5220B Cylindrical	2 2	4,000 4,000		56,000 71,000	14.0 17.7		MoS_2 + Epoxy Binder	8	45,205	95.8
8	SKF 2220CY Spherical EB 5220B Cylindrical	2 2	4,000 4,000		56,000 71,000	14.0 17.7		23 Kt Gold	8	217	0.5

(For explanation of footnotes, see next sheet.)

Figure 7 - ATL LARGE SCALE BEARING (100 MM) TEST RESULTS

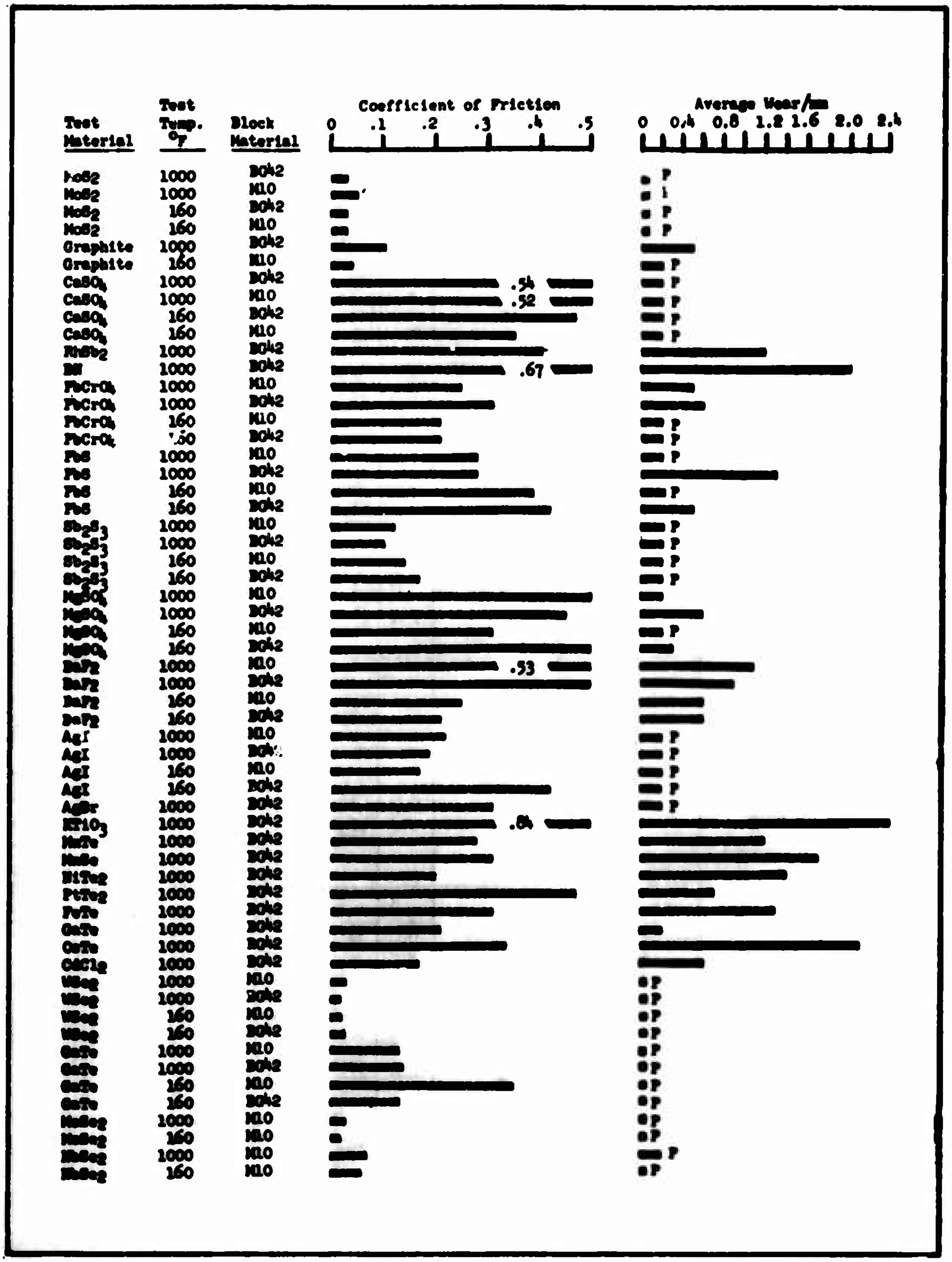
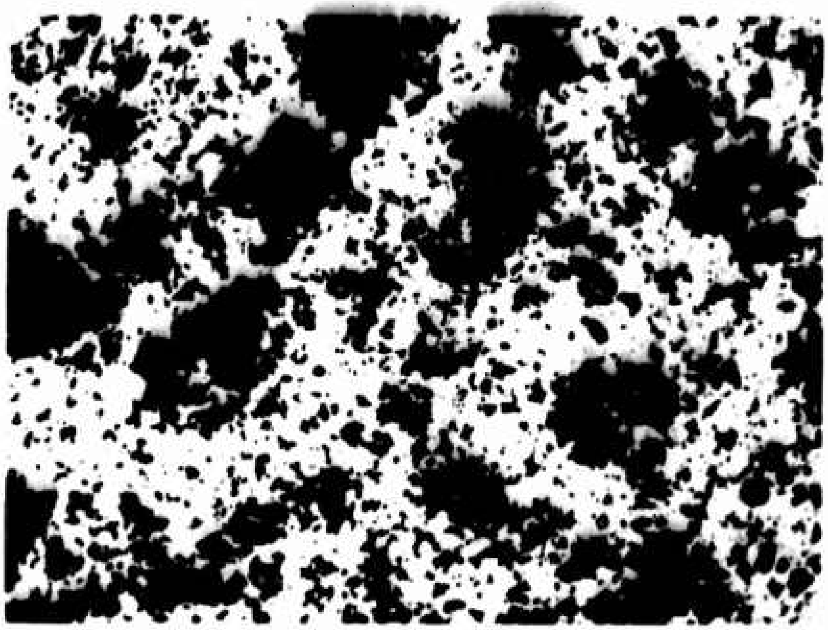


Fig. 8 - Wear and Friction of Powders



a. 22-1/2 PTFE: 7-1/2 $MoSe_2$-70 Silver 100X

b. 30% PTFE: 10% $MoSe_2$-60% Copper 100X

Fig. 9 - Microstructure of Lubricating Composite

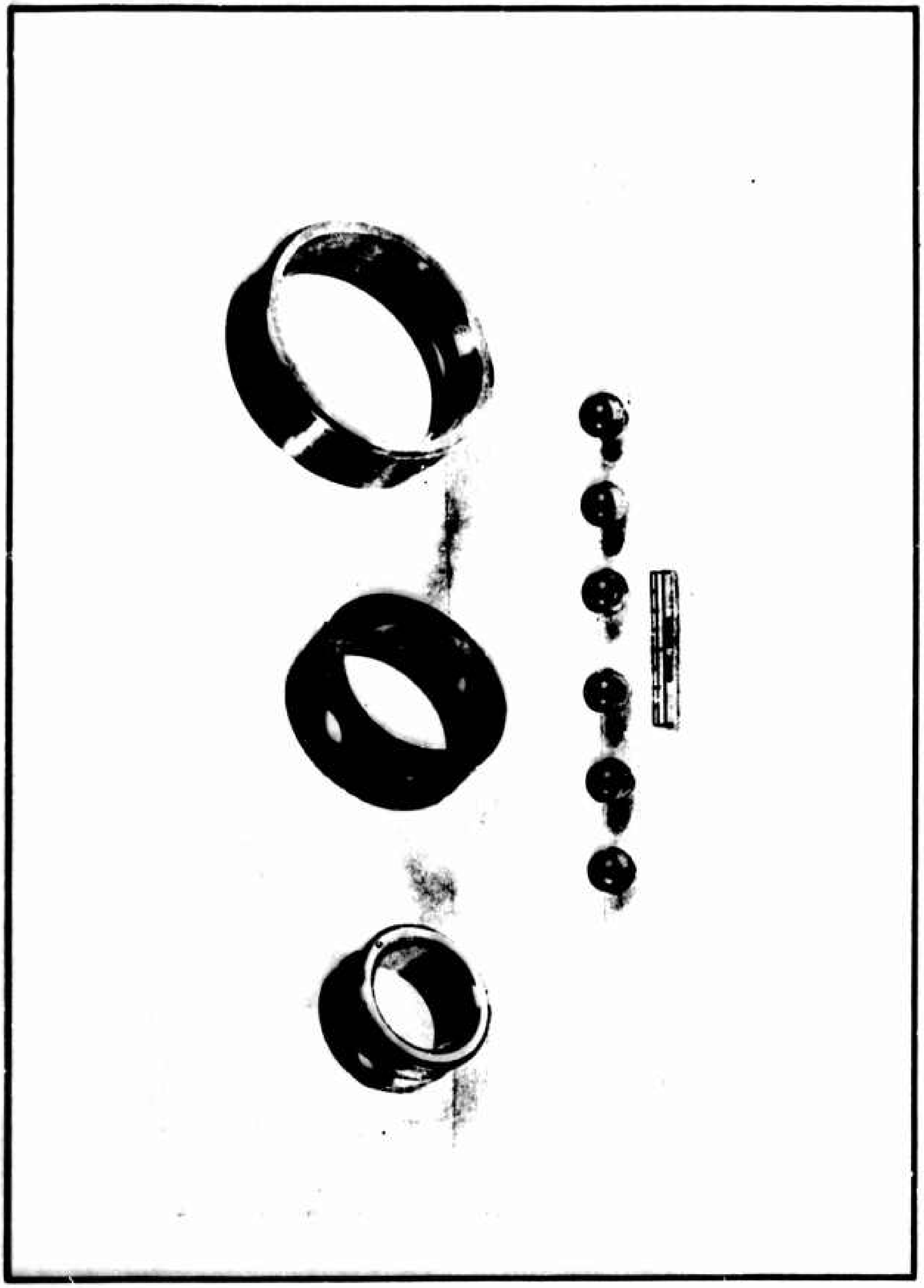


Fig. 10 - Bearing with Duroid 5813 Retainer After 100 Hours Operation; Test 2

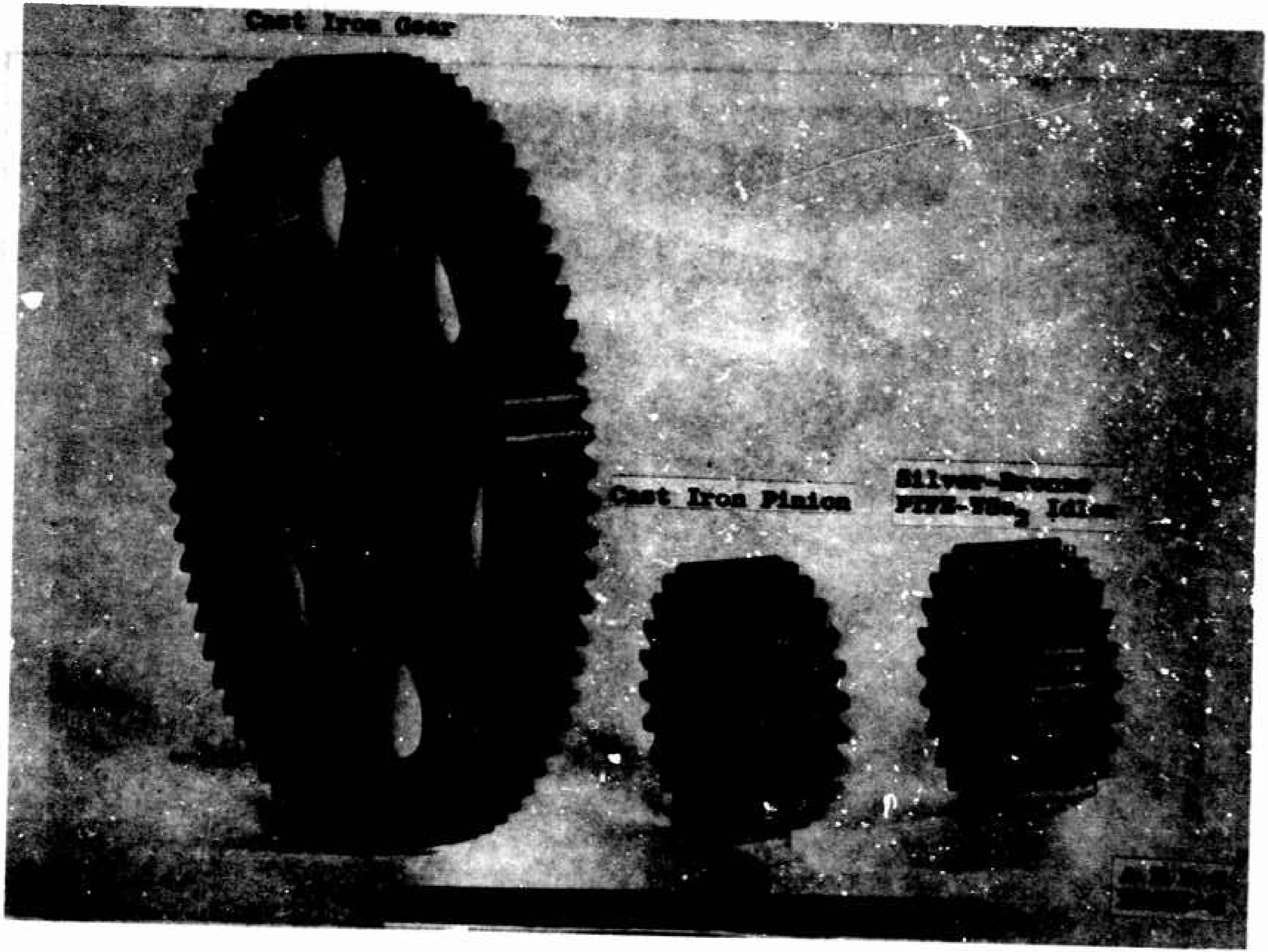


Fig. 11 - Gear, Pinion, and Idler

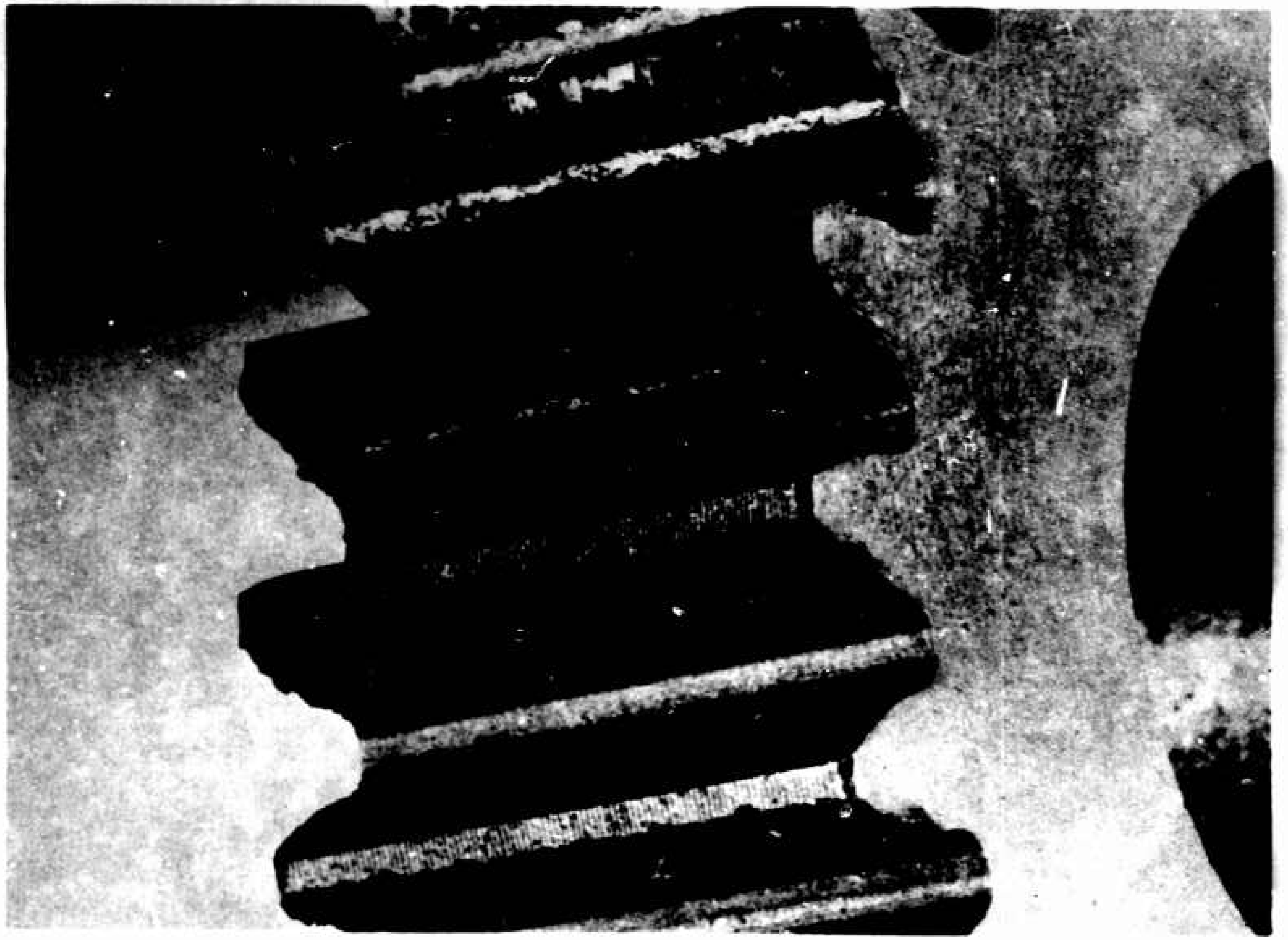


Fig. 12 - Pinion P-105 Failure After 52 Hours Operation - Test 4 - Mag. 5X

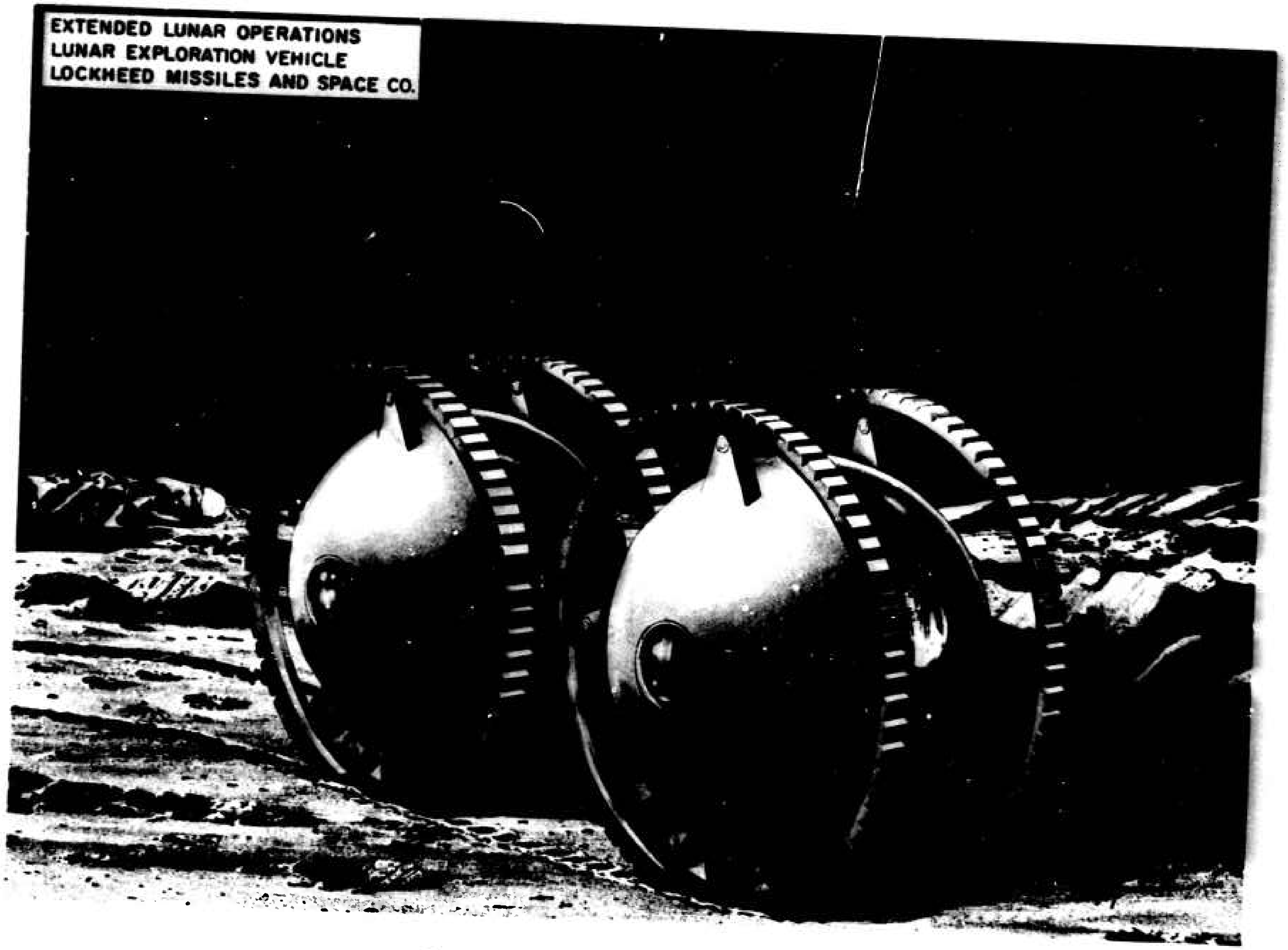


Fig. 13 - Extended Lunar Operations

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A PRELIMINARY SYSTEM CONCEPT
FOR
EXTRATERRESTRIAL MINING AND PROCESSING EQUIPMENT

By Carl B. Hayward

It is generally agreed that once an initial landing is accomplished on the moon attention will rapidly focus on follow-up programs. Following early basing and reconnaissance operations, a second phase program would logically include the development of an improved semi-permanent base and the development of local resources to reduce the logistic burden and dependence on earth for certain basic raw materials.

The successful accomplishment of such a second phase program will depend upon the availability of an efficient lunar mining and ore processing system. In recognition of the importance of this requirement, numerous preliminary study efforts are being initiated to explore and define the problem, and thereby to direct and hasten the necessary advancements in the state-of-the-art.

In the broad overall sense, lunar mining and processing operations are closely related to many other factors (such as the geological, logistic and by-product aspects which are being investigated as separate tasks), but the specific operational functions and principal hardware categories of a real system can be summarized under six general headings.

The initial function in such a system is to obtain a supply of raw ore for subsequent processing. This raw ore will be obtained by rock breaking (stoping) either on or beneath the lunar surface, and will involve drilling and blasting with chemical explosives. The use of nuclear devices and tunnel boring machines have been suggested for lunar excavation, but these methods are not considered feasible for the production of ore. The principal equipment items involved will be a vehicle mounted lunar drilling machine capable of drilling holes several inches in diameter to depths of five to twenty-five feet with high speed and efficiency, and an effective lunar blasting system including special equipment, materials and techniques.

The second distinct function involves the loading of the raw ore after the rock has been broken loose. This operation is one of the most difficult mining operations to mechanize because of the unavoidable variation in rock size and the interlocking and packing effect of random sized fragments. A rugged vehicular type machine will be required for this function and once the ore has been picked up, it should proceed through the entire process without the need of a subsequent 'digging' type operation.

The third distinct function of a lunar mining and processing system is the reduction of the ore to the limiting size required by the processing equipment. This will be accomplished in one or more steps identified as coarse crushing, fine crushing and grinding, depending on the degree of size reduction required. No other requirements in the ore dressing area are foreseen at this time.

Coarse crushing (to not less than $1\frac{1}{2}$ inches) will be accomplished by some form of a jaw-type crusher. In order to minimize and/or virtually eliminate the necessity of hauling, handling and storing raw ore by the use of heavy, ruggedly built equipment, it is necessary that the coarse crusher be mounted on (or at least very near) the primary loading machine and thereby be in a position to accept the ore as it is picked up.

Fine crushing (to not less than 1/8 inch size) can probably be best accomplished in a cone-type crusher. It is probable that this operation will require a gaseous atmosphere to avoid particle rewelding due to the high pressures and large surface areas created by the crusher. A requirement for an atmosphere calls for a pressurized chamber, and this aspect would in turn suggest that the crusher be located in a sealed underground cavern. However, if the mode of operation involves 'open pit' surface mining, then the crusher would have to be designed as a pressurized 'closed' chamber unit and be integrated with the ore processing equipment for operation on a batch basis.

Grinding (reduction below 1/8 inch size) if necessary will definitely require a gaseous or liquid medium to prevent cold welding of the pulverized ore, and for this reason ore grinding should be associated with the ore processing operation. However, both the initial weight and the continuing attrition factors associated with grinding equipment would be extremely difficult to justify from a logistic standpoint, and therefore a requirement for grinding should be avoided if at all possible.

A fourth function involves transportation of the ore from the mining area to the processing area. The crushed ore will be transported in open containers without stockpiling or rehandling; a discharge receiver at the crusher will serve both as a transport container and as a loading hopper at the processing plant. The containers will be moved on wheels, but whether the wheels move on cables, rails or directly on the lunar surface will depend upon the set-up and site conditions of a particular installation. A small holding capacity for containers will be required at each end of the travel route to permit continuous equipment operation, but timing of the entire operation will still be a critical factor.

The fifth distinctive function is the ore processing plant itself. The nature of the equipment will depend upon the type of mineral available, the substance to be extracted and the type of process adopted. A discussion of extraction processes and equipment is quite beyond our scope today, but I can assure you that work has already begun and that progress is being made in this field. In any case, the processing plant will undoubtedly involve a considerable requirement for electrical energy (for either direct or indirect process use) and a need for pressurized equipment operated as a semi-automatic closed loop system.

The sixth and final element of the mining and processing operation is a facility to purify, convert and store the system products until time of use. This facility may recover calylitic or processing mediums for reuse and in other ways purify the final product, recover process heat, liquify gaseous products, provide secondary treatment for by-products, and provide for the storage and system discharge of all the products.

It should be noted that the aspects of equipment weight and logistic burden tend to require a highly optimized system design, a relatively large scale continuous production rate, the development of worthwhile uses for by-products and possibly a degree of equipment interchangeability for processing alternate minerals. Another factor which could simplify many design and weight problems is the possibility of mining and processing the ore in a sealed underground tunnel or cavity with a pressurized atmosphere as opposed to conducting operations on the surface with pressurized equipment.

The ultimate feasibility of lunar and space exploration will depend in large measure upon man's ability to extract necessary useful substances from extraterrestrial resources. The attainment of this capability is contingent upon the successful development of a highly optimized and fully integrated space rated mining and processing system; and work on such a system has already begun.

THE APPLICATION OF SURFACE MOBILITY TO LUNAR MINING OPERATIONS

By Grady L. Mitcham

INTRODUCTION

Studies of manned lunar exploration systems have shown that an important role exists for surface mobility systems in this phase of lunar development. In the transition from lunar exploration to lunar exploitation, it appears that surface mobility system utilization will increase greatly as feasible areas of operation are identified and implemented. An area of major exploitation interest that possesses the potential for developing a substantial transportation requirement is the mining and processing of lunar materials; more specifically, the extraction of water or other rocket propellant or life support material base from lunar rock.

Overall System Considerations

Our lunar exploration and lunar basing studies have identified numerous mobility-related tasks. Various vehicle concepts for accomplishing these mission tasks have been designed and evaluated in the light of our present limited knowledge of the lunar environment and terrain. The results have indicated that surface vehicle systems are feasible solutions to the problem of accomplishing many of the tasks.

Surface vehicle systems may be applied to many phases of the mining and processing operation. Some of the areas where possible mobility requirements exist are:

- Transporting processing plant and excavating equipment from the landing site to the operational area.
- Providing mobility for excavating or mining equipment.
- Movement of the ore to the processing plant.
- Delivery of the processing plant output to the point of utilization.
- Logistics support of the operation, including mining and processing outpost resupply and personnel rotation.

Each particular mining-processing program postulated must be studied as a whole to establish optimum system requirements. The determination of surface mobility requirements are a part of this task. There are several considerations that affect these requirements.

The location and extent of suitable ore bodies would be an important factor. Bodies of suitable ore may be small and widely dispersed. Conversely, perhaps large expanses of surface aggregate exist which contain sufficient quantities of the desired material to justify processing. In the former case, a system utilizing a large central processing plant and ore-carrier vehicles may be the answer. In the latter, mobile processing equipment with an excavating attachment could be optimum. In some cases, conveyors may suffice if distances are short.

The richness of the ore could affect the decision whether to select a system using ore carriers with a central plant or to use multiple on-site plants with output transporters.

The scope of the total program is a vital consideration. Producing water, oxygen, and hydrogen to support a limited lunar base would certainly generate a different set of requirements from those for producing rocket propellant for a moon-launched manned Mars expedition.

Figure 1 relates general mission tasks that could be performed by surface vehicle concepts as the lunar program expands. This chart suggests that systems should be defined with growth or adaptability in mind.

Vehicle Conceptual Aspects

The selection of vehicle conceptual approach depends to a great extent on the variety of tasks and the scope of the total lunar program. One aspect of conceptual approach analysis is the comparison of specialized versus general purpose equipment.

Where a task or activity is frequently or continuously performed, a vehicle designed specifically for that task usually will demonstrate superior performance and economy. The specialized approach creates a family of limited application designs, however the subsystems can be optimized around a fairly specific set of requirements. Large scale operations usually will justify the development of this type of equipment. For example, a mobile processing plant would perform poorly as a crew transporter.

On the other hand, general purpose concepts are intended to perform the largest variety of tasks with a minimum number of basic vehicle types. With this approach, lower development costs, smaller vehicle inventories, and a high level of utilization are the goal. A basic general purpose vehicle cannot be expected to perform all required tasks without supplementary equipment to extend the basic capability. By providing special attachments, the vehicle can be adapted to perform many tasks with reasonable efficiency.

Another approach to the adaptation of surface vehicles for increased versatility is the use of a modular system. Through this concept, a vehicle can be converted for varying or increasing mission requirements. Personnel transporters could have provisions for installing crew cab and life support modules of different capacities. Power supply modules, including fuel storage could be changed to suit the job at hand. The limiting factor for the adaptability of a given vehicle is the size and load capacity of the basic chassis.

MANNED LUNAR PROGRAM-SURFACE VEHICLE TASKS

EXPLORATION ▶	BASE CONSTRUCTION ▶	MINING AND PROCESSING
• CREW MOBILITY • CREW SHELTER	• CRFW MOBILITY • CREW EMERGENCY SHELTER	• CREW MOBILITY • CREW ROTATION • CREW EMERGENCY SHELTER • RESCUE
	• EXCAVATION AND EARTH MOVING	• ORE EXCAVATION • ORE LOADING • ORE TRANSPORTATION
	• SHELTER AND REACTOR TOWING	• PROCESSING PLANT RELOCATION • PLANT ERECTION
	• RESUPPLY SPACECRAFT UNLOADING • MATERIAL TRANSPORT	• TRANSPORT OF PLANT OUTPUT TO CENTRAL SITE • RESUPPLY SPACECRAFT UNLOADING • RESUPPLY OF REMOTE SITES

FIGURE 1

SPECIALIZED VEHICLE CONCEPTS

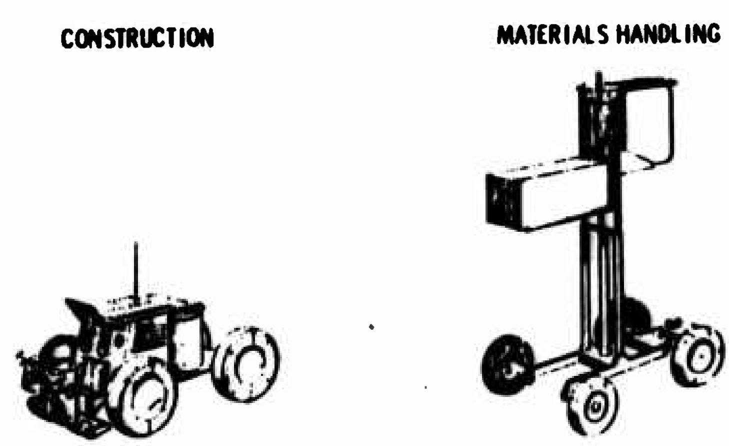


FIGURE 2

Lunar base and lunar exploration studies performed by The Boeing Company have investigated a number of surface vehicle concepts. Many of these show applicability to some phase of mining and processing operations and could be considered to be transitional designs, forerunners of the larger designs that would evolve with expanded programs. Figure 2 shows examples of two highly specialized concepts studied for performing lunar base implementation tasks. The construction vehicle is designed to excavate and collect loose, fine lunar surface material and throw it to a designated area. The specific mission tasks are nuclear reactor burial and shelter module shielding using surface material. The equipment installed at the vehicle forward end consists of a helical cutter-collector, an elevating helix and a gravel throwing belt. The material is collected and thrown as the vehicle moves along the surface. Also included in the design is a two-man cab.

The material handling vehicle is on the right. This concept is specifically designed to unload large resupply packages from the payload deck of a Saturn 5 Logistics Vehicle, transport the packages to the shelter module, and elevate the packages to the airlock level, which is 7.1 meters above the lunar surface, for unloading. The heaviest Logistics package has a mass of 2140 kilograms. The control cab accommodates one man. Since the total energy expended while unloading an entire logistics payload is small, the vehicle is battery powered.

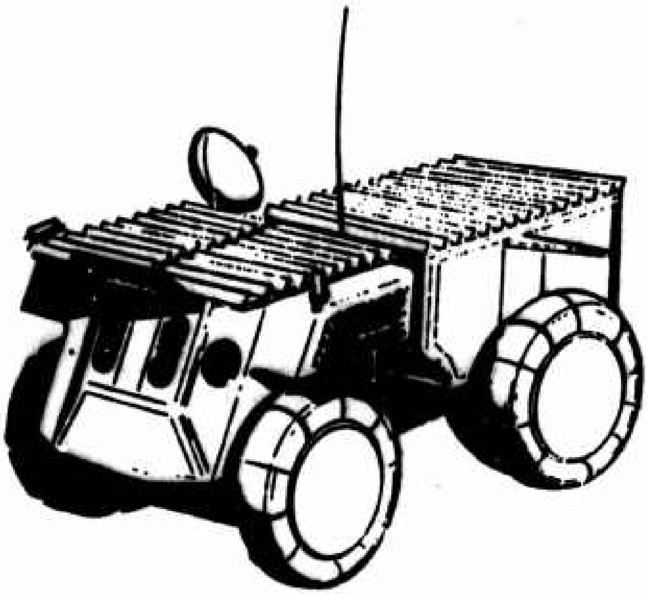
Examples of adapted general purpose vehicles are shown in Figure 3. The basic concept is an exploration vehicle suitable for a four-man crew. The forward section is the crew cab; the aft unit contains the fuel cell power system, storage tanks for the liquid oxygen and liquid hydrogen fuel cell reactant, life support oxygen and surplus water storage. To adapt the vehicle for materials handling, a flatbed trailer is installed at the forward end of the vehicle. Since the trailer is not equipped to lower or elevate payloads, this function must be provided at the loading and unloading points. The construction adaptation includes an excavation attachment installed on the forward end and a towing attachment for shelter moving at the aft end. Conversion of the vehicle for extended exploration requires a trailer containing supplementary power equipment, fuel cell reactant and life support oxygen. The extended exploration vehicle depicted in Figure 3 suggests a possible ore-carrier configuration composed of a control cab-power section with a cargo trailer train.

Vehicle Design Considerations

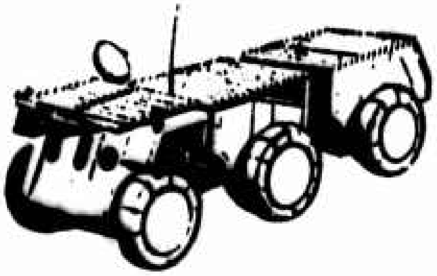
In the design of a surface vehicle, one of the more important considerations is the selection of the mobility concept. The question of wheels versus tracks often arises when vehicle conceptual designs are studied. Other approaches, such as walking or jumping machines do not demonstrate any general advantage over the conventional systems and appear to create some very difficult design and operational problems. Figure 4 compares wheels and tracks on the basis of general mobility criteria. It is surprising to some that wheels show a definite advantage over tracks, especially when soft soils and rough terrain are anticipated.

The degree of mobility required depends both on the known characteristics of the lunar surface over which the vehicle will operate and the degree of uncertainty.

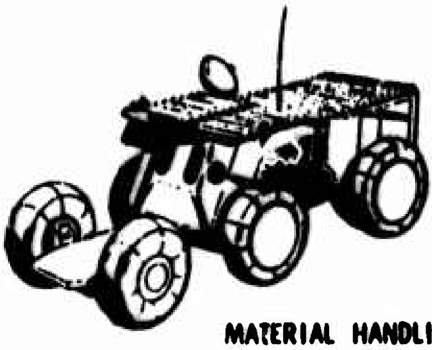
GENERAL PURPOSE VEHICLE ADAPTATION



LOCAL & INTERMEDIATE EXPLORATION

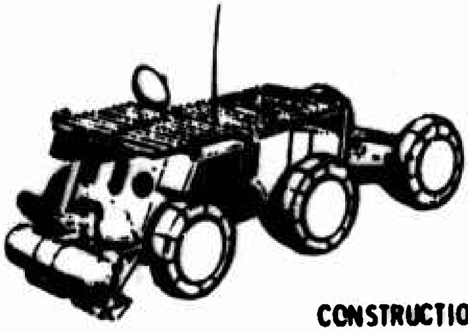


EXTENDED EXPLORATION



MATERIAL HANDLING

MISSION	VEHICLE MASS - KG
LOCAL EXPLORATION	3550
INTER. EXPLOR.	4370
EXTENDED EXPLOR.	6350
CONSTRUCTION	4290
MAT'L HANDLING	3590



CONSTRUCTION

FIGURE 3

If the terrain and surface conditions over which the vehicle must operate are well known, and the task sequences defined, an optimized system may be designed. A particular case would be that of a tanker vehicle that would operate over a prepared roadway between the processing plant and a fixed base. Conversely, vehicles required to traverse unknown or rough terrain must compromise other performance to favor extreme mobility. The primary power and drive system design must provide the capability for obstacle negotiation. Vehicle dynamics studies indicate that the combination of low lunar gravity and surface roughness will require that vehicles operate at relatively low velocities to prevent loss of control or upset. However, the reduced gravity offers a distinct operating advantage. Since locomotive power and energy requirements are basically a function of weight on the wheels and velocity, large payloads may be moved at a relatively low power and energy cost. This aspect will favorably support the development of lunar mining programs.

An example of the low power demand is demonstrated by the large extended exploration vehicle of Figure 3. With a gross mass of 6350 kilograms, the average locomotive power at 5 kilometers per hour is only 2.6 kilowatts.

COMPARISON OF TRACKED AND WHEELED VEHICLES

CRITERIA	REMARKS
SOFT GROUND CROSSING CAPABILITY	TRACKED VEHICLES ARE ONLY SLIGHTLY SUPERIOR IN DRY GRANULAR SOILS
STEP OBSTACLE CAPABILITY	WHEELED VEHICLES CAN BE DESIGNED FOR MUCH GREATER CAPABILITY THAN TRACKS
CREVICE CROSSING CAPABILITY	APPROXIMATELY EQUAL
WEIGHT	TRACKED VEHICLES ARE HEAVIER
RELIABILITY	TRACKED VEHICLES USUALLY HAVE POOR RELIABILITY
EFFICIENCY	TRACKED VEHICLE EFFICIENCY IS LOW

FIGURE 4

A problem area that is ever-present is the severe lunar environment. Equipment may be subject to constant meteoroid bombardment, and temperature extremes and the hard vacuum present unique design challenges. Vehicle maintenance presents very difficult problems; however, equipment life is a valuable commodity with the cost of vehicle delivery so high. The feasibility and economics of providing environmentally controlled maintenance facilities requires study. Crews must be protected from the environment including radiation and furnished life support. This requirement can create a heavy penalty. Unmanned vehicles utilizing remote control or automation, especially where repeated traverse of the same path occurs, should be considered.

Feasibility studies of mobile excavating and loading equipment merit particular attention. The low lunar gravity and system power budgets will challenge the application of many existing earth-utilized concepts; however, the low gravity field will reduce loads,

power, and energy. Low mass is a mandatory property of space delivered hardware, yet high mass is a usual characteristic of earth-type equipment not employing tie-downs to provide reaction forces. New, imaginative excavation concepts utilizing explosive force or impact energy are in order.

Concluding Remarks

In this short discussion, we have superficially examined what appears to be a potentially broad aspect of the lunar exploitation field. A great deal of work lies ahead in developing a sufficient understanding of where and how mobility may be best used to support mining and processing operations. It is important that surface vehicle studies be performed in conjunction with investigations of mining and processing systems, and that these comprehensive studies consider the elements of the entire lunar program, including:

- Interplanetary launch support objectives
- Lunar exploration plan
- Lunar basing objectives
- Delivery systems
- Funding

References

1. Dr. M. G. Bekker, Mechanics of Locomotion and Lunar Surface Vehicle Concepts, Automotive Engineering Congress, January 14-18, 1963, Detroit, Michigan.

2. The Boeing Company, Analysis of Lunar Surface Vehicles for Lunar Exploration Systems for Apollo, Contract NASw-902, D2-100134, July 15, 1964.

DISCUSSION

COL. PETERS: In addition to what we said before, the thing that concerns me more than the bearing problem, is the seal problem. Any time you have equipment which is crushing rock, you are going to have a lot of small particles and with our cold welding and sticking effects up there together with the vacuum, I think this is going to be quite a problem around vehicles and machinery. They are going to have a tendency to collect this material and from time to time we are going to have to brush off, shake off or somehow get rid of it. And, of course, we are going to have to have bearings, quite a few of them, in addition to the wheel bearings around machinery. All of these will have to be protected from this dust which is just literally pouring all over this equipment all the time. I think the seal problem is potentially more troublesome than the bearing problem.

MR. HAYWARD: There was one other comment, too, to the general effect that there was a relationship between the location or establishment of a mining operation and the base. I think there very definitely is a very close relationship from the standpoint not only of hauling but also using the finished products from the processing plant. There is also the relationship of the personnel with the operation of the mine. I think there is a close relationship here in that the proposed location for any base of operation should be selected with some reference to the availability of these resources of which we might make use.

COL. PETERS: I know that Jack Salisbury is doing some work right now at the Martin Space Flight Center trying to determine if there is some way you can keep dust or small particles from adhering in a vacuum. Maybe we can have him tell us a little bit of his progress. I don't know if he has made any progress or not.

DR. SALISBURY: I haven't.

QUESTION: I wonder if you gentlemen have come to any general conclusion about how closely you can locate this processing plant to its a site.

MR. HALL: I think you have hit a dull point. Does anyone care to answer this question from the audience? Have you any ideas?

UNKNOWN: Well, maybe what I had in mind wasn't too clear, but the problem exists of navigation of lunar space craft between the landing site and the proximity of such a mine.

MITCHAM: I would say that we have considered this, in answer to your particular question on the navigation problem. There are studies in process with the Bendix Company under contract to NASA and Boeing Company with the Bomarc contract which does preclude navigation on the lunar surface over a given mission profile which might vary as much as 50 to 75 meters away from where the vehicle has land .. I think there are many approaches to this and I am not really at liberty to disclose the results of these studies because the contract has not yet been finished. But, the navigation as a whole on the lunar surface doesn't seem to be too difficult. In fact I think it is a much simpler problem than probably

getting to the moon itself. Landing a vehicle or logistics type vehicle that might be carrying mining equipment or a mobile vehicle of the type shown, probably can be landed within the proximity of the LEM or within a radius of possibly a quarter of a mile. This, of course, means that you do have an active transport between the two vehicles.

VISITOR: If a visitor can ask a question here, I noticed the discussion, a little bit ago,of the relative cost of carrying large weights to the lunar surface versus the cost of man hours on the lunar surface. Now, is it not true that once a spaceport or base is established to the extent where at least a reasonable proportion of the consumables are produced on the surface, hydroponics or whatever, and production of water and oxygen from lunar rocks, and so forth-at that point allowing a reasonable stay time for a worker, will not the cost of labor per man hour go down drastically from that which has been stated earlier, so that at that time it will then be less costly to do much of the work on the moon rather than to go through the process of transporting these extremely heavy objects from earth to the moon?

HAYWARD: I agree with you completely. If you have a large installation there that is self-sustaining, still there is going to be the problem of relocation of men from the lunar surface to the earth. Now I think this is a point of conjecture. Many people have different opinions as to how long a man can stay on the lunar surface. I know that in some of our studies we intended to rotate the men on about a six months basis and this is one of the things that really runs the cost of your system up quite a bit. Now these are the kind of things that need to be studied in great detail and I think that these are the types of programs that will be thought about. This could bring down the cost, and, of course, again depending on the launch system you use, and it's payload capacity.

FEASIBILITY OF LIQUID HYDROGEN PRODUCTION ON THE LUNAR SURFACE

P. E. Glaser
A. E. Wechsler
J. H. B. George

I. INTRODUCTION

In the paper presented at the 1963 Annual Meeting of the Working Group on Extraterrestrial Resources we discussed the types of water deposits, environmental factors, energy sources, and extraction processes using mined deposits.[1] In the following sections the production of liquid hydrogen is considered in its broader aspects including in situ extraction processes, electrolysis of water, liquefaction of hydrogen, and long-term storage of liquid hydrogen.

II. WATER EXTRACTION PROCESSES

A. BACKGROUND INFORMATION

Several types of water extraction processes for use on the moon have been described by Salisbury[2] and Wechsler, et al.[1,3] Extraction processes can be classified as in situ processes and processes using mined deposits; the type of process selected will depend upon the types and locations of the deposits actually found on the moon.

An in situ extraction process can be defined as one in which the water is extracted from the deposit in its original location; mining and/or transport of the deposit would not be required. An example of this type of process (in terrestrial use) is the Frasch process for sulphur recovery. In the Frasch process, superheated water is forced underground into the sulphur deposit; the sulphur melts and flows to the surface with the water stream. In situ extraction processes for large deposits of hydrated minerals or permafrost may be attractive because mining and transportation costs would be greatly reduced. However, drilling, emplacement of heat sources, sealing of the formations to prevent undesirable movement of fluids, possible capping of formations to provide pressurization, and other aspects of in situ extraction present technical problems which will require considerable study and analysis. A detailed knowledge of the geology of the underground deposits will certainly be required for in situ processes, and considerable prospecting would probably be involved. On the other hand, surface processes using surface or underground deposits may require complex mining and transportation techniques.

B. WATER EXTRACTION PROCESSES

In the initial attempts toward water extraction on the moon, materials available on or close to the surface probably will be processed in small devices. As lunar technology is developed, water extraction processes may require surface vehicles to transport rock to a processing plant which uses kilns or fluid bed reactors. These processes have been discussed in the literature.[1,3] In this paper, therefore, we shall discuss only in situ methods which will become more important when large quantities of water are needed.

We have evaluated in situ extraction processes by choosing an analytical model which depicts a typical process, specifying the type of lunar water deposit, and calculating maximum production rates of water as a function of geometry, energy input, temperature and variables associated with the types of deposits expected.[4]

Any process for in situ water extraction which utilizes a continuous underground heat source has been considered by us to be a variation of the "Frasch" process. The energy may be derived from an underground heat source such as a nuclear reactor, radioactive isotopes, electrical heaters, and liquid metal heat exchangers. We have assumed that heat sources can be represented by cylindrical or spherical shaped systems. Depending upon the type of heat source, the process may operate at a constant temperature or produce a constant heat flux. If the source operates at a constant rate, its temperature will vary during operation; the maximum temperature of the source will be limited by materials of construction and the type of heating device.

Consider the analytical model shown schematically in Figure 1. A spherical heat source of radius R_0, operating at constant temperature or constant power, is surrounded by an infinite mass of rock. As heat diffuses outward from the source, the temperature of the rock is raised. When the temperature of the rock reaches a critical value, T_c (the dehydration, vaporization, or melting temperature, which will depend upon the type of deposit), the water held in the rock is released and collected at the surface. In the analysis, we have not considered the manner in which the water flows as vapor or liquid to the surface. The maximum water production will be obtained if all the water released within the rock can be collected. A sharp spherical interface of radius R separates the water-bearing deposit and the dehydrated deposit. The interface, which represents a moving heat sink, moves outward with time as more rock is heated and water produced. In both rock zones--i.e., those containing water and those in which water has been removed--heat is transported by conduction. If the rate of growth of the interface with time can be determined, the rate of water production can be established.

Similar models may be established for a cylindrical heat source at constant temperature or constant heating rate, as indicated in Figure 1. We have considered systems where the length of the cylinder is large compared to its radius.

Several assumptions have been used to simplify the calculations:

1. The deposit surrounding the heat source is homogeneous (initially) and at a constant initial temperature.

2. The thermal properties of the deposit are isotropic and are specified by the density, specific heat, thermal conductivity, and thermal diffusivity.

3. The water content of the deposit is uniform throughout the structure.

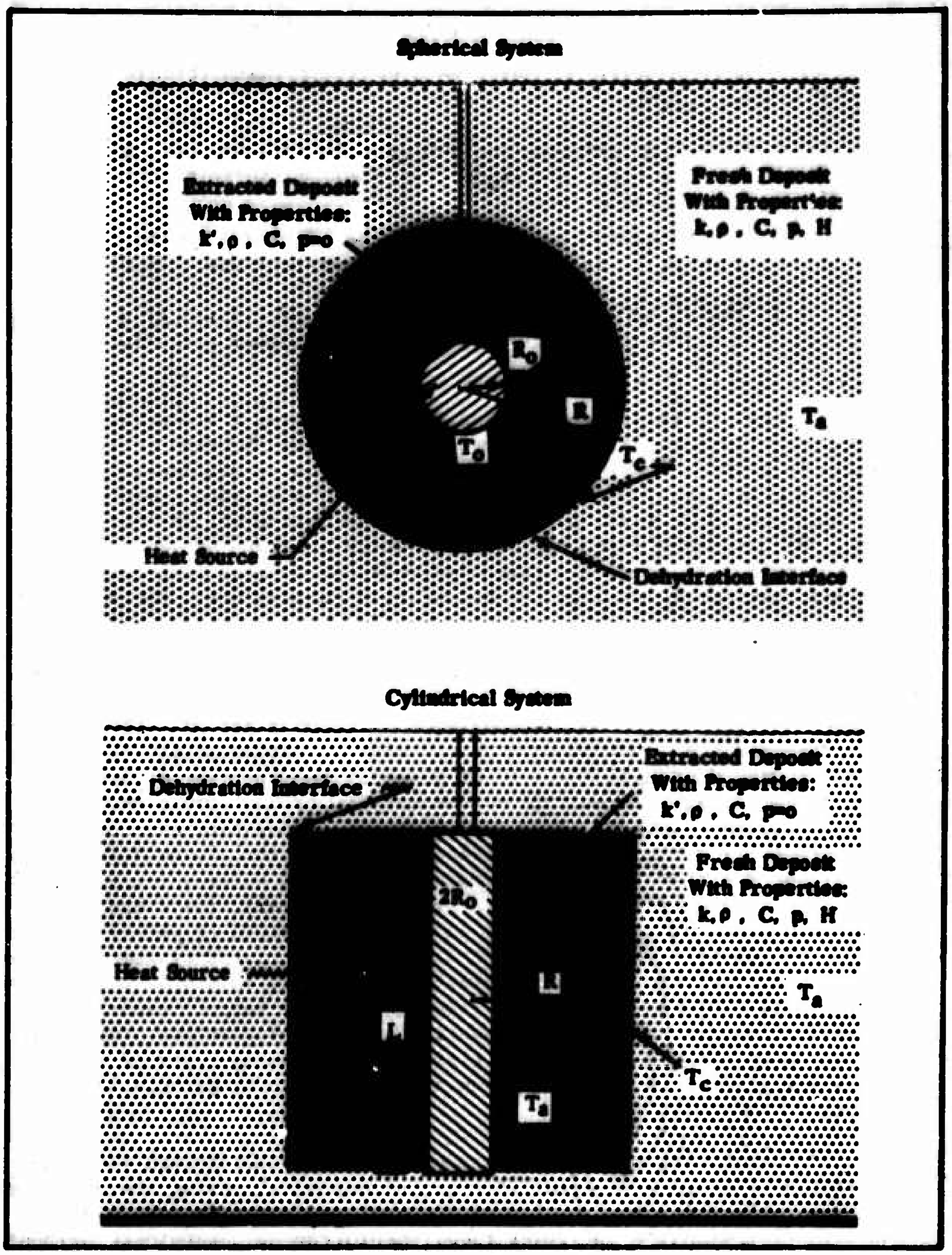


FIGURE 1. ANALYTICAL MODELS FOR WATER EXTRACTION CALCULATIONS

4. The dehydration, melting, or vaporization temperature of the deposit and the heat required to produce the desired phase change have a constant value throughout the system.

5. After dehydration, the dehydrated media may have a different thermal conductivity and diffusivity than the virgin material.

6. The spherical heat source can be maintained either at a constant temperature or at a constant power input.

7. The cylindrical heat source can be maintained at a constant temperature or at constant power per unit length.

The problem of determining the rate of water production as a function of the physical and thermal properties of the deposit can be formulated mathematically, but a general solution is difficult to obtain without the use of a computer. However, simple analytical solutions have been obtained for several particular cases which are of practical significance. We have considered the cases in which the heat of vaporization is much smaller than, of the same magnitude as, or much larger than the sensible heat of the rock at the dehydration temperature. The detailed results of the calculations are available in the literature.[4]

In order to compare the practicality of several typical systems for in situ dehydration, we have assumed that an average of eight pounds of water per hour is to be produced over a two-year period. (The total water produced over the two-year period will be approximately 140,000 pounds.) Depending upon the type of geometry and the type of deposit considered, the production rate may be uniform or may vary considerably over the two-year period. Four typical types of deposits have been considered: (1) a rock containing 1% water which is loosely held (by physical absorption, for example), (2) a rock containing 1% water which is strongly held (for example, in the form of a hydrated mineral), (3) a hydrated rock containing 10% water, and (4) an ice-sand mixture or permafrost containing 40% water. The important characterisitcs of the systems are shown in Table I. Specific heat and thermal conductivity values were chosen as representative of the data in the literature. The heat of vaporization or dehydration is an important quantity in the calculations; these values have not been determined with great precision for many types of rocks. The values given here are based upon the data given by Brindley[5] and others.

Other values of these parameters can be substituted for consideration of other more specific types of deposits. Using the parameters given in Table I and the results of the analyses described above, the operating temperatures and power requirements can be determined for heat sources of various radii and length.

TABLE I

CHARACTERISTICS OF TYPICAL SYSTEMS FOR WATER EXTRACTION PROCESS EVALUATIONS

Deposit	Water Content (%)	Density (gm/cm^3)	Water Vaporization: Temperature (T_c)(2) (°C)	Water Vaporization: Heat of Vaporization (cal/gm)	Specific Heat (cal/gm-°C): 100°C	Specific Heat: T_c	Specific Heat: 1200°C	Thermal Conductivity (cal/sec-cm-°C) x 10^3: 100°C	Thermal Conductivity: T_c	Thermal Conductivity: 1200°C
Rock	1	2.7	100	540	0.20	0.21	0.22	7	7	6
Hydrated Rock	1	2.7	600	600 - 1100	0.20	0.21	0.22	7	7	6
Hydrated Rock	10	2.6	600 - 700	600 - 1100	0.25	0.23	0.22	6	5	4
Permafrost(1)	40	2.0	0 - 100	675 - 540	0.20	0.21	0.22	3	3	3

(1) Permafrost melts at 0°C with heat of fusion of 80 cal/gm. Specific heat and thermal conductivity at 0°C are assumed to be 0.32 cal/gm-°C and 6 x 10^{-3} cal/sec-cm-°C, respectively.

(2) The ambient temperature was assumed to be -40°C for all systems.

For example, in the first type of deposit listed in the table, the sensible heat of the rock is significantly greater than the heat of vaporization. If a spherical heat source of 5-ft radius is used, a temperature of approximately 1290°C is required to produce water at an average rate of 8 lb/hr. For a 7-ft radius heat source, the heat-source temperature is found to be 890°C. The power required (at the end of the two-year period) is estimated to be approximately 80 kw for heat sources of either radius. (An ambient temperature of -40°C was used for these calculations.)

Similar calculations were carried out for each of the four systems described in Table I, for both spherical and cylindrical geometry systems operating at either constant temperature or constant power. The results of the calculations are shown in Tables II and III. A value of 800 cal/gm was chosen for the heat of dehydration for the rocks containing 1% and 10% water of hydration. A vaporization temperature of 600°C was chosen for the rock containing 1% water of hydration, and 650°C was chosen for the rock containing 10% water of hydration. A vaporization temperature of 100°C was used for permafrost with a heat of vaporization of 600 cal/gm.

Tables II and III show which systems may be practical for consideration in water extraction processes and give estimates of the required input power and heat source temperatures. Extraction of water from a rock containing 1% water as a hydrated mineral would be impractical with reasonable size spherical heat sources, because of the very high temperatures required. A cylindrical heat source may be more practical; however, the operating temperatures are still high, which may lead to material problems.

The most desirable system would be permafrost, because of the high water content and the relatively low temperatures required for hydration. Water can be extracted from 10% hydrated rock with reasonable temperatures and power inputs if cylindrical heat sources or large spherical sources are used. For the production requirements considered above, a heat source 10 feet in diameter and 100 feet high, operated at 1000°C, would be required. The power required would be 370 kw at the end of the two-year period. This is a very large heat source and may be impractical since a hole would have to be drilled in the deposit to accommodate the source. Also, this requires that the deposit be at least 100 feet thick.

The general conclusion obtained from these examples is that although the power requirements for the process are reasonable and, for some cases, the temperatures required are well within the present state of the art, large size heat sources are required. This would involve considerable difficulty in emplacement of the source. Moreover, problems with gas flow and sealing the formation would probably increase as the radius and length of the heat sources are increased. Other calculations can be carried out for any specific system using the techniques discussed above and described in detail elsewhere.[4]

TABLE II

TYPICAL RESULTS OF WATER EXTRACTION CALCULATIONS

Basis: Spherical geometry, 8 pounds water per hour (140,000 pounds averaged for 2 year period)

System	Radius of Source (Ft)	Constant Temperature Heat Source: Temperature (°C)	Constant Temperature Heat Source: Power[(1)] (kw)	Consta Power Heat Source: Temperature[(2)] (°C)	Consta Power Heat Source: Power (kw)
Rock 1% Water	5	1290	80	1350	85
	7	890	80	930	88
Hydrated Rock 1% Water	7	4200	--	>4200	--
	10	2740	--	>2740	--
Hydrated Rock 10% Water	5	2700	123	2800	125
	10	1400	136	1400	142
Permafrost (Vaporization) 50% Water	3	690	12.6	640	11.8
	5	324	12.2	330	12.6

(1) Power required at end of 2 year period.

(2) Temperature at heat source radius at end of 2 year period.

TABLE III

TYPICAL RESULTS OF WATER EXTRACTION CALCULATIONS

Basis: Cylindrical geometry, $L = 20\ R_o$, 8 pounds water per hour (140,000 pounds averaged for 2 year period).

System	Radius of Source (Ft)	Constant Temperature Heat Source: Temperature (°C)	Constant Temperature Heat Source: Power (kw) (1)	Constant Power Heat Source: Temperature (°C) (2)	Constant Power Heat Source: Power (kw)
Rock 1% Water	2	570	83	820	62
	4	300	117	360	74
Hydrated Rock 1% Water	3	1900	460	2300	300
	5	1200	580	1500	380
Hydrated Rock 10% Water	3	1300	230	1400	130
	5	1000	370	1100	210
Permafrost (Vaporization) 50% Water	1	175	2	130	2.5
	3	130	5	105	2.5

(1) Power required at end of 2 year period.

(2) Temperature at heat source radius at end of 2 year period.

As an alternative to the continuous heating process for in situ water extraction described above, step heating processes should also be considered. Consider the detonation of a nuclear device of small yield, e.g., one kiloton, within a water bearing deposit. If the device is placed sufficiently below the surface, the radioactivity can presumably be contained underground, the cavity formed by the explosion will not reach the surface and venting will not occur. Within the initially formed cavity, there is a mass of molten and vaporized rock, steam, and fission products. Part of the energy release from the explosion will be absorbed by vaporization and melting, part will be transferred to the surroundings by compressional waves, and part will remain in the radioactive products within the cavity. If the water initially vaporized within the cavity could be transported to the surface without condensation, this type of process might be an attractive method for water production on the moon. After the initial vaporization occurs, heat flows from the cavity into the surrounding deposit at a rate determined by the thermal properties of the deposit and the size and temperature of the initial cavity. As a result of the gradual heating of the surrounding material, additional water could be produced in a manner similar to that described above for continuous heating processes.

We have carried out a simplified analysis of the initial and long-term heating accompanying underground explosions in typical water deposits.(4) According to the work of Johnson, et al,(16) the initially melted rock which is converted to glass on cooling amounts to about 500 $\pm$ 150 tons per kiloton of released energy. About 30% of the total energy released by the explosion is initially deposited in the steam and hot rock formed in the cavity. Using this data we estimate that in deposits initially containing 1 and 10% water, 10,000 and 100,000 lbs of water could be produced initially. The production would of course depend upon sophisticated methods for conducting the steam to the surface before condensation and redistribution throughout the formation would take place.

For a one kiloton explosion, by assuming that the temperature of the initial cavity was in the order of 1200°C, and the rock had a dehydration temperature of 650°C, we estimate the additional water production after the initial explosion could amount to 13,000 and 110,000 lbs for initial moisture contents of 1 and 10%, respectively. The general conclusion for other yield nuclear devices is that the gradual release of water after the explosion would be of approximately the same magnitude as the initially released water. The calculations indicate that most of the gradually released water would be produced within the first several months after the explosion.

The step heat processes described above have been simplified for the purpose of obtaining preliminary estimates of water production. More detailed calculations should be carried out when additional information from underground nuclear explosion tests are made available.

III. ELECTROLYSIS OF WATER

Electrolysis appears to be the most likely process for obtaining hydrogen from water produced by a suitable extraction process. The design of an electrolyzer for use on the surface of the moon will, therefore, figure importantly in considering the logistics burden for liquid hydrogen production.

Presently available commercial electrolyzers have been designed to obtain a reasonable compromise between low first cost and low operating costs, the largest single factor in the latter being power consumption.(6) They tend to be heavy and bulky and use steel as a material of construction. In the United States, electrolysis for hydrogen production is not a major technology since vast quantities of waste hydrogen are available at oil refineries. Electrolysis is used only in special circumstances, where either small capacity output or high purity hydrogen is desired, or when power costs are extremely low.

Operations on the surface of the moon present a totally different set of requirements. The source of energy for the electrolyzer would most likely be a nuclear reactor. Since power consumption would have to be minimized, the electrolyzer would have to operate efficiently. In addition, weight would have to be greatly reduced since the electrolyzer must, at some stage, be part of a payload in a space vehicle. Environmental factors, particularly the extremes of temperature, high vacuum, and exposure to radiation will influence the design. The low lunar gravity will present secondary problems in the engineering design of an electrolyzer.

To design an electrolyzer for use on the moon, the electrochemical data available for the electrolytic decomposition of aqueous solutions at a variety of electrode surfaces will have to be re-examined. Of particular interest is the behavior of the lighter metals as gas-producing electrodes. Corrosion problems probably will be too severe for such electrode materials to be used directly, but possibly, light metals covered with a thin cladding of noble metal foil might be used. The electrode might be modified further by covering it with a layer of platinum black, a surface showing minimum overvoltage for gas evolution.

Another area of importance is the physical design of the electrodes and their configuration relative to each other. The evolution of gas bubbles increases the resistance between the electrodes; in a good design bubbles would be released rapidly to minimize this effect. Reduced gravity will be an important problem here, since bubble rise time is proportional to $g^{-1/2}$. The technology of fuel cell electrodes should be considered and work already carried out applied to this design.

The requirement for low resistance and minimum corrosion points towards the selection of an aqueous alkali as the best electrolyte. However, the choice of concentration and temperature of operation would need to be optimized in concert with the choice and design of the electrode system.

For materials of construction, glass-fiber reinforced plastics appear to be good candidates on the basis of their high strength-to-weight ratios. Relevant technology has already been developed in the fuel cell field. Numerous secondary materials problems will have to be overcome, e.g., in connection with the requirement for adequate seals.

The design of an electrolyzer will be influenced by the methods chosen for the hydrogen liquefaction process which may determine the required throughput rate. This rate will influence the volume of electrolyzer required, the maintenance to be supplied and the overall system reliability.

IV. HYDROGEN LIQUEFACTION

The liquefaction of hydrogen obtained from the electrolytic process has to be accomplished by cooling the hydrogen until its sensible heat has been removed and its condensation temperature is reached. The final step in liquefaction requires the removal of the latent heat of vaporization. In principle, the thermodynamics of the refrigerating process are very well understood; however, the inefficiencies of practical refrigeration processes require complex designs for liquefiers to minimize these inefficiencies.

The liquefaction of hydrogen can be based on well established techniques with considerable background available from the experience gained in the operation of industrial plants producing 30 tons of liquid hydrogen a day and from design studies of space-borne refrigerators now reaching the prototype stage. In a technical sense, therefore, the design of hydrogen liquefiers for use on the lunar surface should present fewer obstacles as compared with other developments required for the successful operation of a lunar base.

The lunar environment will influence the design of a hydrogen liquefier in three important ways. First, the temperature excursions experienced by objects on the lunar surface, ranging from 105°K to 390°K, require that parts of the liquefaction apparatus be designed to withstand these temperature changes. Second, the effects of hypervelocity impacts by micrometeoroids will lead to changes in absorptivity-emissivity characteristics of any exposed surfaces and pose an additional hazard of penetration of such surfaces. Finally, dust particles may cover exposed radiating surfaces and change their radiating effectiveness.

These environmental influences can be expected to modify some of the basic design approaches but are not expected to present insurmountable problems.

To operate successfully, the hydrogen liquefier will have to perform for extended periods without requiring attention from an operator or complex maintenance. The choice of components for the liquefier will have to be guided by the requirements for minimum weight and maximum reliability with a development lead time of up to ten years. Because of

the schedule by which the liquefier will be required, it may be assumed that adequate power supply systems will be available and that optimization procedures based on minimizing weight in addition to power will be appropriate.

A. LIQUEFACTION PROCESSES

The following two basic processes can be considered:

1. High-Pressure Process

Figure 2 shows the flow diagram of a hydrogen liquefier which utilizes Joule-Thomson liquefaction with precooling of the incoming gas. Purified hydrogen at a pressure of about 100 atmospheres is supplied to the liquefier by a compressor. The flow of gas is divided between two heat exchangers. In the first heat exchanger, the incoming high-pressure hydrogen is cooled by the low-pressure hydrogen gas returning to the compressor; in the second heat exchanger, it is precooled by the precooling liquid. The stream of partially cooled hydrogen then passes through another heat exchanger filled with the precooling liquid and finally enters a Joule-Thomson heat exchanger cooled by the returning stream of unliquefied hydrogen. At the bottom of this last exchanger is the Joule-Thomson expansion valve which reduces the pressure of the hydrogen gas to near atmospheric, causing part of the hydrogen to be condensed in a reservoir, while the remaining gas is returned via the other heat exchangers back to the compressor. The liquefier section is provided with a catalyst to produce liquid parahydrogen and thus reduce the losses which would otherwise be encountered by the spontaneous exothermic conversion of the 75% orthohydrogen in the liquid.

Because the hydrogen gas would be made through the electrolytic process, precautions would have to be taken to insure that only pure hydrogen reaches the liquefier. Otherwise, contaminating gases may solidify and obstruct the passages of the liquefier and particularly the JT expansion valve. Small oxygen impurities could present explosion hazards inside a high-pressure hydrogen liquefier when solid oxygen accumulates within high-pressure hydrogen gas tubes.

The precooling liquid which in a conventional high-pressure hydrogen liquefier is liquid nitrogen could be replaced with another liquid having a higher boiling point but below 240°K. 240°K corresponds to the conversion temperature for the Joule-Thomson effect. Expansion through the JT valve will not produce cooling unless the hydrogen is precooled below this temperature. The advantage of using a precooling fluid with a higher boiling point than that of nitrogen would be to allow it to be passed through a heat exchanger on the lunar surface where such a fluid could be cooled below 240°K by operating during the lunar night.

The high-pressure liquefaction process would require the development of an efficient high-pressure hydrogen gas compressor, but this appears to be within the state of the art.

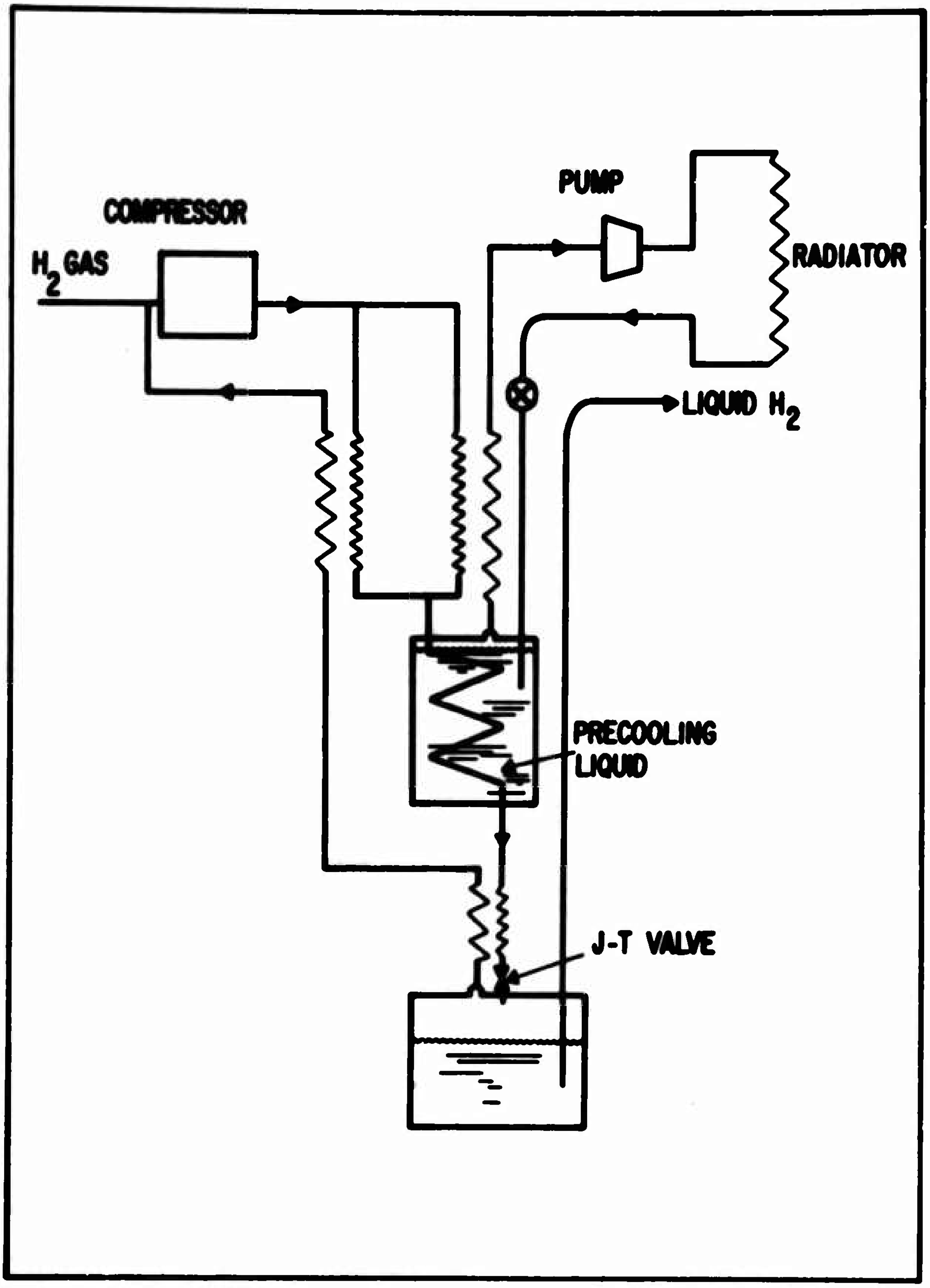


FIGURE 2. HIGH PRESSURE LIQUEFACTION PROCESS

2. Low-Pressure Liquefaction Process

Low-pressure liquefaction is an attractive alternative process. In this process, which has been used successfully to liquefy helium, work is extracted from the system by means of expansion engines, thus reducing the energy content (and therefore the temperature) of the gas. The gas is then further cooled by means of a Joule-Thomson expansion. The combination of JT expansion and expansion engines can provide more refrigeration per unit of power and per unit of gas circulated. Its drawbacks are that more complex machinery is required which would lead to an increase in development effort for use of such a process on the lunar surface.

Rotating machines for the expansion devices are lightweight, reliable, and have a long maintenance-free life, and appear to be best suited to carry out gas compression and expansion for the liquefaction process. Reciprocating expansion engines which have been successfully used tend to require a higher weight and may be the source of possible contamination of the gas stream. Turbocompressors and expanders can be integrated into a system operating at low pressure ratios and utilizing efficient thermodynamic cycles for the liquefaction process. A typical flow diagram for the low-pressure process is shown in Figure 3. A helium loop incorporating a compressor and two stages of expansion engines is used to obtain refrigeration. In a separate loop hydrogen is cooled in heat exchangers and liquefied by expansion through a JT valve.

To achieve good component efficiencies, the expanders will have to operate at speeds in the order of 200,000 rpm. The use of gas bearings is mandatory when such high speeds have to be achieved. Because the working fluid can be used as a gas lubricant, contamination by other lubricants and bearing materials is thereby largely eliminated.

The design of the radiator will be dictated by the conditions found on the lunar surface, and a detailed optimization procedure will have to be carried out to indicate whether continuous operation or operation during the lunar night is preferable. For example, the coefficient of performance is about four times higher during the lunar night. The design of the liquefaction processes optimized with respect to the overall weight and desired efficiencies is within the state of the art. Several such design efforts are now in progress.[7,8,9,10]

A typical requirement for power and output for a liquefaction process is shown in Table IV. In general terms the high-pressure liquefaction process utilizes a less efficient cycle than the low-pressure process and requires more power and larger radiating areas. Mechanical design of components for the high-pressure process may be more straightforward.

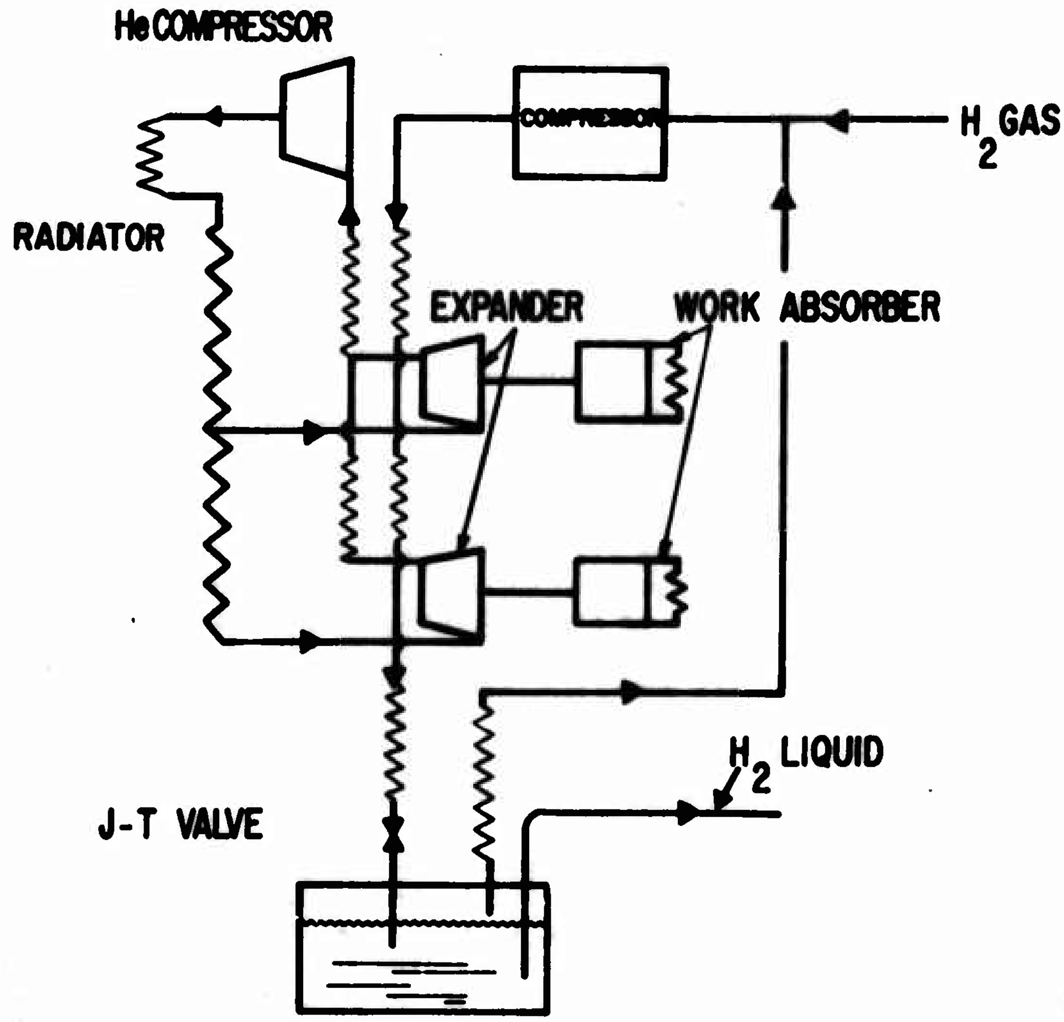


FIGURE 3. LOW PRESSURE LIQUEFACTION PROCESS

TABLE IV

TYPICAL CHARACTERISTICS OF HYDROGEN LIQUEFIER

(Expansion Engine Cycle)

Reversible Work Requirements = 2 kw-hr/lb

Actual Shaft Work Requirements ≅ 8-10 kw-hr/lb

Ratio of Shaft Work to Heat Extraction ≅ 70:1

Weight of Industrial Plant
(Exclusive of Power Supply) ≅ 300-600 lb/kw

Estimated Weight of Lunar Plant
(Exclusive of Power Supply) ≅ 70-140 lb/kw

V. STORAGE OF LIQUID HYDROGEN

Whether the liquid hydrogen is produced continuously or intermittently by a specific liquefaction process, significant quantities of liquid will have to be stored for extended periods. The size of storage tank required will be governed by the specific lunar exploration or lunar orbit refueling requirements. It may be desirable to store liquid hydrogen for periods in excess of one year so that larger quantities can be accumulated using a liquid hydrogen production plant of fixed output capability. To provide a year's storage capacity for the output of a plant liquefying at the rate of about one pound per hour would require a tank with a diameter of about 16 feet. A diagramatic representation of the tank placed on the lunar surface is shown in Figure 4.

A. LOCATION

It is possible to consider two locations for the tank: buried underground or above the lunar surface. The underground location has the advantage that the tank is not subjected to the extreme temperatures during a lunation and that it is protected from the effects of meteoroid impacts. However, the advantage of a subsurface location has to be weighed against the possible difficulties of excavation and installation of the tank. Detailed information which will be obtained on the nature of the subsurface materials and further studies of excavation and mining equipment will guide the selection of the type of location.

Because the above surface location appears at this time to be the most feasible, studies are being made of the parameters governing the design of a liquid hydrogen storage tank located on the surface of the moon.

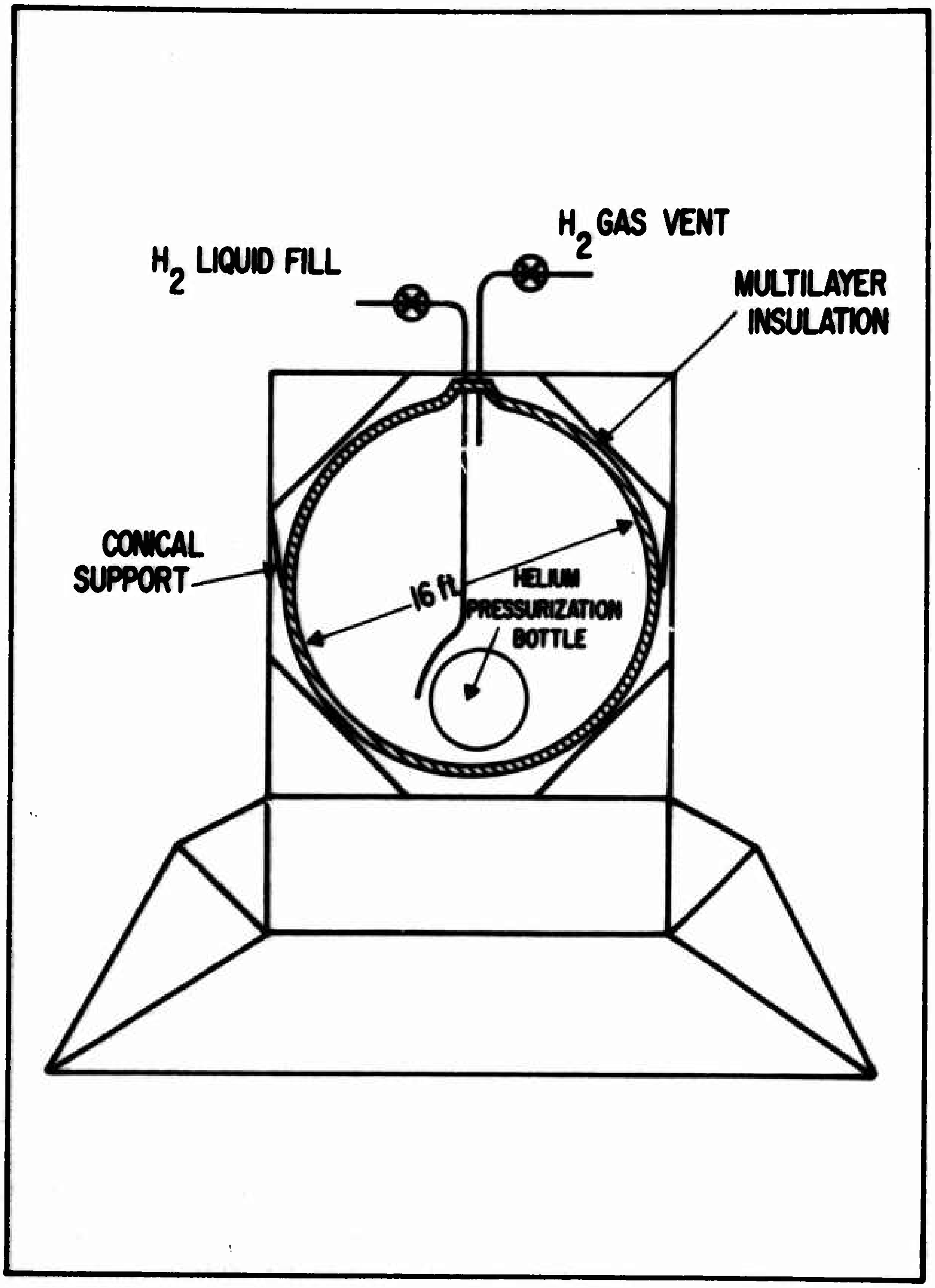


FIGURE 4. CRYOGENIC STORAGE TANK ON THE LUNAR SURFACE

B. HEAT TRANSFERRED TO THE TANK

The heat exchange between the storage tank and its environment can be divided into two parts: (1) the heat received by the outside shroud enclosing the storage tank and (2) the heat exchange between the shroud and the storage tank.

The external shroud of the storage tank will receive direct solar radiation, radiation reflected from the lunar surface, and radiation emitted by the lunar surface and surrounding objects. The shroud will radiate energy to the spatial environment, which can be considered to be a radiation sink approaching absolute zero. In addition, the shroud may exchange heat with the lunar surface at points of contact with it.

Photometric evidence indicates that the lunar surface reflects radiation according to a distinct lunar back-scattering law which may influence the radiation heat exchange between the tank and the surface.[11] The emittance-absorptance characteristics of exposed surfaces may be subject to change with time because of erosion of temperature control coatings by hypervelocity impacts and by dust deposition. To reduce the heat exchange between the environment and the external shroud, the use of external radiation shields is indicated. The effectiveness of radiation shields has already been recognized and promises to be of particular value on the lunar surface. Figure 5 shows the two types of shields required. One shields the shroud from direct solar radiation and the other isolates the shroud from radiation emitted and reflected by the lunar surface.

An analysis of the effectiveness of such shields indicates that the surface temperature of an external shroud may approach temperature values nearly as low as those during lunar night when both types of shields are used.[12] (See Figure 6.) Because solar radiation is not falling on the shroud, the ratio of solar absorption to emittance will have a small effect on the shroud temperature, thereby reducing the influence of undesirable environmental changes on these characteristics. Therefore, from a thermal point of view, the above surface location may be preferable to a subsurface location because subsurface temperatures do not fall below about -40°C.

The external shroud may be designed to form the micrometeoroid shield. Information is being obtained which indicates that the effects of direct micrometeoroid impacts can be dealt with adequately by a thin shield spaced from the shroud. As yet unknown are the effects of secondary impacts of debris reaching the shroud from materials thrown out by primary meteoroid impacts with the lunar surface. Since the velocity of these secondary particles will be significantly lower than that of the primary impacts, they will tend to penetrate the micrometeoroid shields, which rely on the vaporization of the impacting particle at hypervelocity speed. Such secondary particles could penetrate the shroud and damage the storage tank. The frequencies, velocities, and trajectories of such secondary particles will have to be established to obtain an indication of the probability of catastrophic impact with the storage tank.

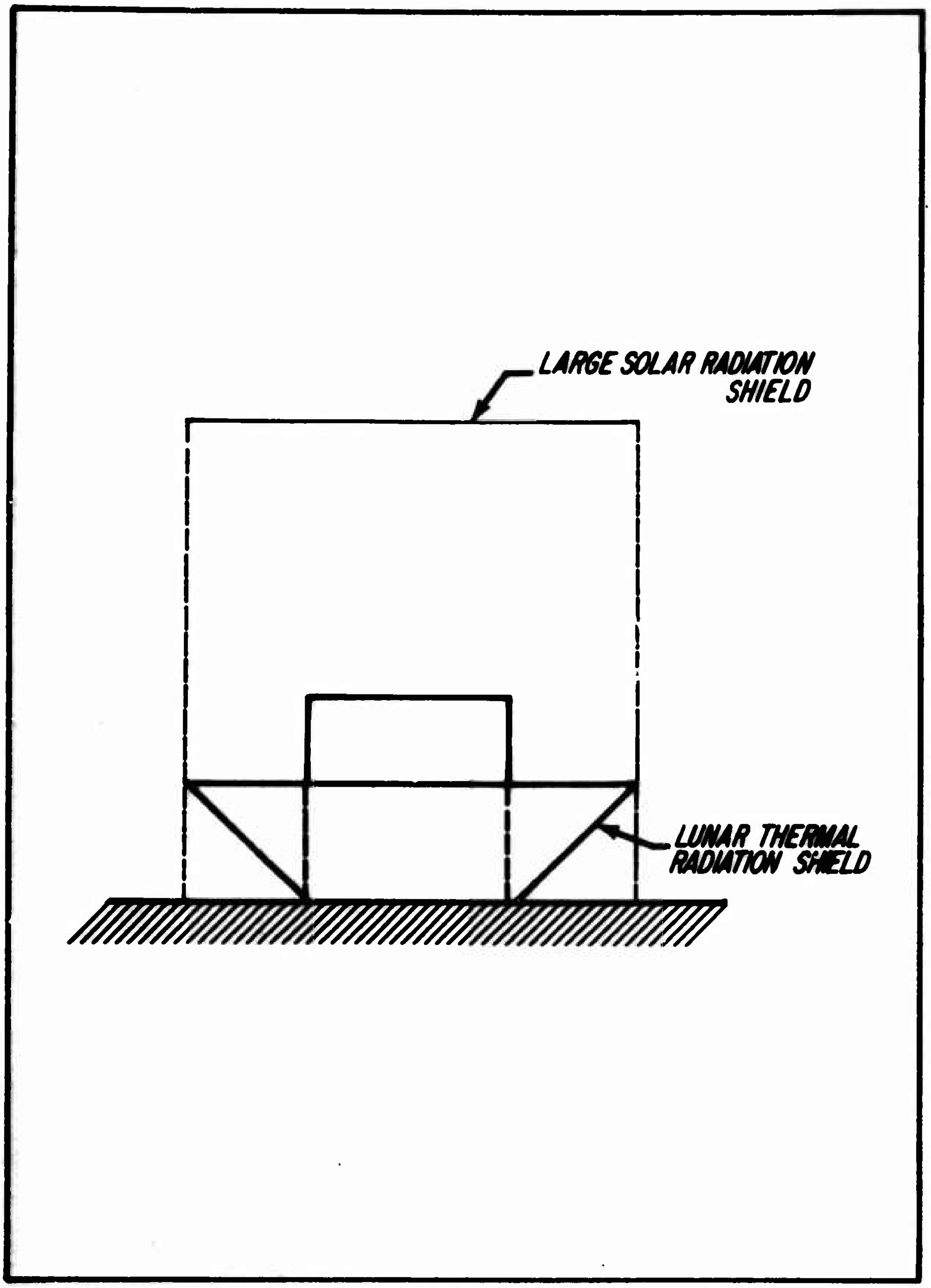


FIGURE 5. ARRANGEMENT OF SHADOW SHIELDS[12]

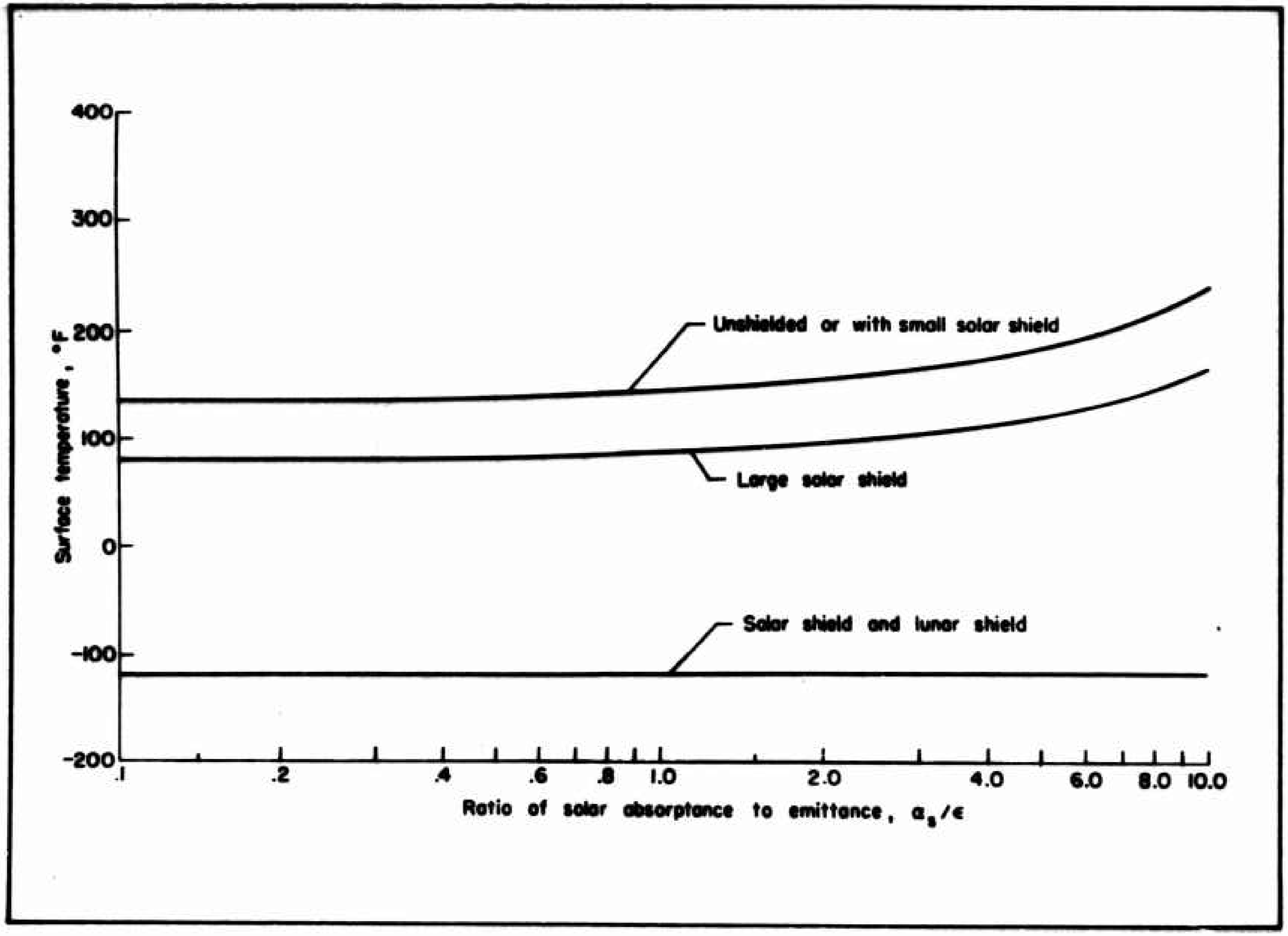


FIGURE 6. EFFECTIVENESS OF SOLAR AND LUNAR RADIATION SHIELDS(12)

Once the temperature of the external shroud has been established, the tank design--in terms of the suspension, insulation and fill and vent lines--can proceed. Of utmost significance to the successful storage is the availability of high-performance multilayer insulations. Table V lists typical multilayer insulation combinations and indicates their thermal performance.(13) Practical application requirements resulting in mechanical loads and penetrations may degrade this insulation performance. Figure 7 indicates the important effect mechanical loads have on insulation performance. An advance in technology will be required to assure that the tank itself can be made leak-tight so that gas pressures within the insulation are below at least 10^{-5}torr.

The effects of penetrations due to structural supports and fill and vent lines can be greatly reduced by providing heat stations and making the most efficient use of the sensible heat of boil-off gases.

The size of supports connecting the storage tank to the shroud will depend on whether the tank is designed to carry liquid hydrogen from the earth to the moon or be delivered to the moon empty. If the tank has to carry fuel from the earth a more substantial support may be required to withstand acceleration and vibration loads. Once installed on the lunar surface, the supports need only be strong enough to suspend the tank in the lunar gravity field. For a storage tank such as that shown in Figure 4, supports a few thousands of an inch in thickness will be sufficient and if suitably insulated will contribute only a fraction of a per cent of boil-off per year in heat leak.

C. AUXILIARY REFRIGERATION

Based on an extension of present technology, it appears to be feasible to construct a storage tank for liquid hydrogen where the boil-off rate would be below 5% per year. In terms of the weight of liquid being considered, the boil-off might be of the order of 400 pounds of hydrogen. Although the total boil-off rate is quite small in terms of our present experience with liquid hydrogen vessels, the total weight of liquid hydrogen lost is significant. To further reduce these losses it may therefore be of interest to consider supplying auxiliary refrigeration to eliminate boil-off gases completely.

The refrigerator weight required to handle various heat leakage rates to the tank is shown in Figure 8.(14) For small heat leakage rates, the weight of the refrigerator (including its power supply) may be attractive when compared with the loss of liquid hydrogen. For storage periods in excess of one year, the use of a refrigerator would have a definite advantage particularly if power is available to meet the refrigerator power requirement. The design of refrigerators has already proceeded to the prototype stage(15) and indications are that, in the design of liquefaction processes, no extreme technological difficulty should be encountered.

TABLE V

COMPARISON OF SEVERAL IMPORTANT MULTILAYER INSULATION SYSTEMS

Insulation System Description		Properties at Optimum Density				Properties at 15 psi Load
Sample Number	Sample Type	Heat Flux $\frac{BTU}{hr\text{-}ft^2}$	K Thermal Conductivity $\frac{BTU\text{-}in}{hr\text{-}ft^2\ F}$	ρ Density $\frac{lbs}{ft^3}$	$K.\rho$ $\frac{BTU\text{-}in}{hr\text{-}ft^2\ F} \times \frac{lbs}{ft^3}$	Heat Flux $\frac{BTU}{hr\text{-}ft^2}$
2026	(10)Smooth aluminum 0.0005" thick & (11)Fiberglass mat 0.014" thick	0.1	0.0001	4.5	0.00045	--
2028	(10)Embossed aluminum 0.0005" thick and (11)Fiberglass mat 0.014" thick	--	--	--	--	13.
1058	(10)1145-H19 Aluminum 0.002" thick & (11)CT-449 material 0.02" thick, 9.0 lb/ft³ density	0.12	0.00014	9.3	0.003	21.
2038	(10)1145-H19 Aluminum 0.002" thick & (11)CT-449 material 0.02" thick, 9.0 lb/ft³ density. Spacer cut to provide only 11% support area.	0.08	0.0007	9.6	0.0007	5.5
3027	(6)Aluminized polyester film 0.00025" thick & (7)CT-449 material 0.08" thick, 12.7 lb/ft³ density. Spacer cut to provide only 11% support area.	0.31	0.00068	--	--	2.3 (Extrapolated)
1054	(20)Crinkled aluminized polyester film 0.00025" thick	0.23	0.00023	1.8	0.00037	Very High
3005	(10)1145-H19 Aluminum 0.002" thick & (11)Vinyl coated glass fiber screen 1/8 x 1/8" mesh & 0.02" thick	0.18	0.00018	15.1	--	Very High

TABLE V (Cont'd)

Insulation System Description		Properties at Optimum Density				Properties at 15 psi Load
Sample Number	Sample Type	Heat Flux $\frac{BTU}{hr\text{-}ft^2}$	K Thermal Conductivity $\frac{BTU\text{-}in}{hr\text{-}ft^2\ F}$	ρ Density $\frac{lbs}{ft^3}$	K.ρ $\frac{BTU\text{-}in}{hr\text{-}ft^2\ F} \times \frac{lbs}{ft^3}$	Heat Flux $\frac{BTU}{hr\text{-}ft^2}$
1064	(10)Polyester film 0.00025" thick double aluminum coated on both sides & (11)Polyurethane foam, freon blown, 0.02" thick, 2.7 lb/ft^3 density	0.12	0.00017	1.2	0.0002	15.
1065	(10)Polyester film 0.00025" thick double aluminum coated on both sides & (11)Polyurethane foam, freon blown, 0.02" thick, 2.7 lb/ft^3 density	0.08	0.00008	0.83	0.00007	2.0
2040	(10)1145-H19 Aluminum 0.002" thick & (11)Nylon netting 0.007" thick	0.09	0.00005	15.1	0.00075	55.
1043	(10)Aluminum 0.001" thick & (10)Glass fiber paper 0.003" thick	0.20	0.00012	3.1	0.00037	110.

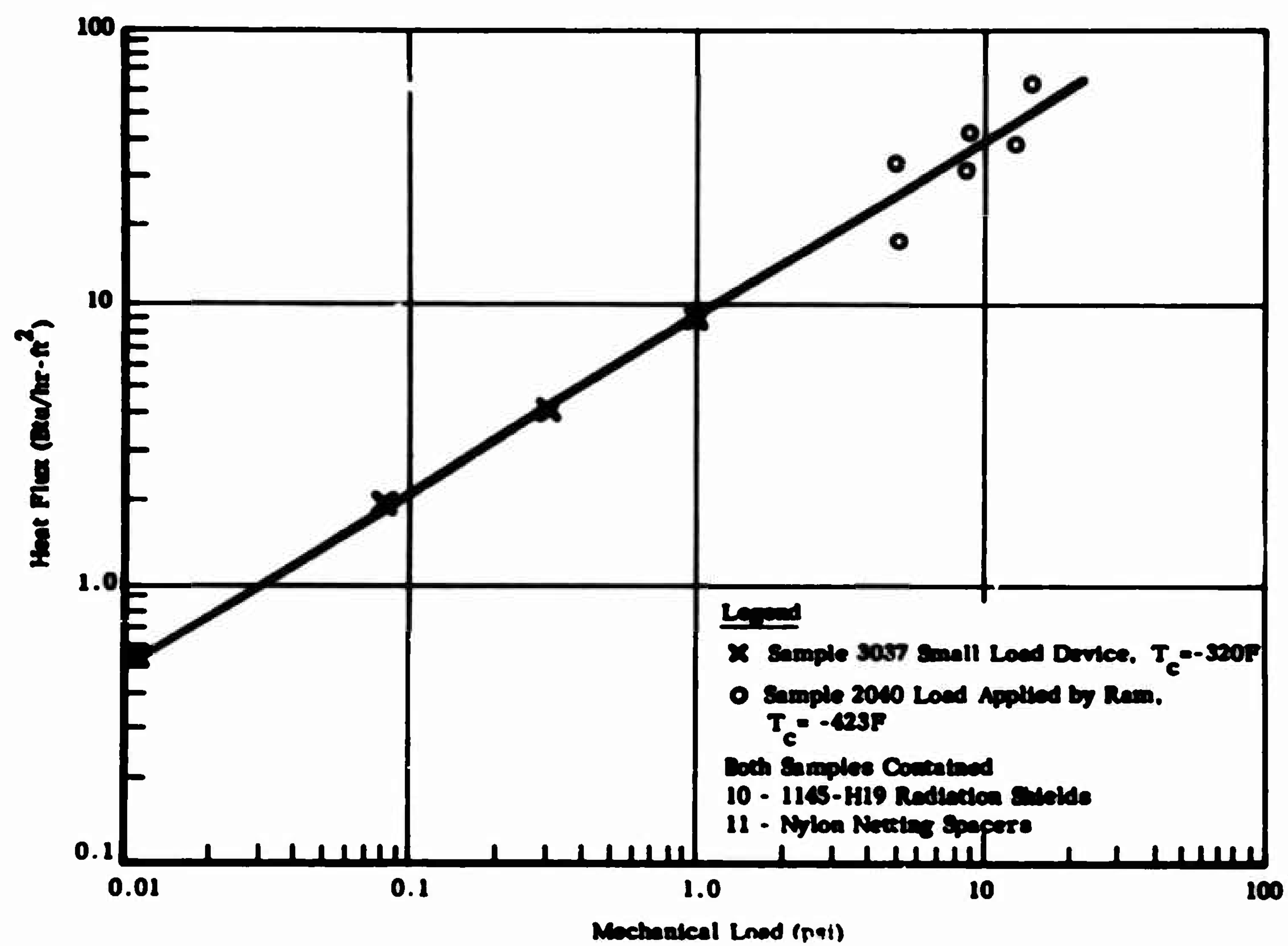


FIGURE 7. EFFECT OF MECHANICAL LOAD ON HEAT FLUX OF MULTILAYER INSULATION

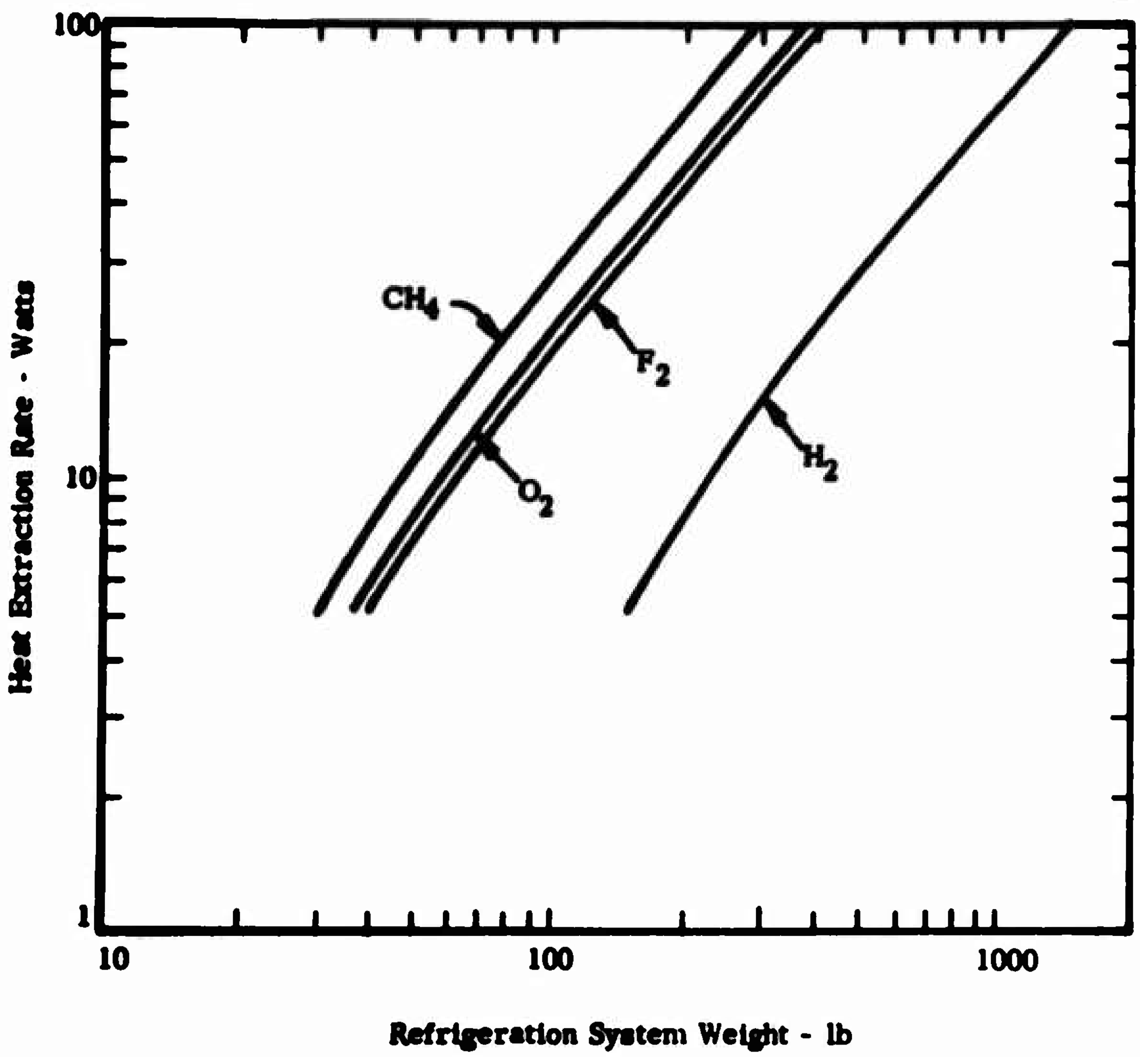


FIGURE 8. ESTIMATED WEIGHTS OF SPACEBORNE RECONDENSING SYSTEMS FOR CRYOGENIC PROPELLANTS

VI. SUMMARY

The following statements summarize our present considerations on the production of liquid hydrogen on the lunar surface:

1. Water can be extracted from lunar water resources provided deposits containing approximately 1% water and occurring in significant quantities can be located.

2. The engineering feasibility of both in situ processes and processes using mined deposits is promising. Detailed investigations of the economics of water extraction and justification of selection of a specific process must still be carried out.

3. Processes using mined deposits appear to be exploitable within a reasonably short time after the first lunar landing is accomplished.

4. In situ extraction processes will require the support of a large lunar base operation with complex technological capabilities.

5. Basic information exists on the principles of electrolysis of water; however, detailed design studies and development of materials suitable for use in lunar-based electrolyzers have yet to be accomplished.

6. Extrapolation of present hydrogen liquefaction processes indicates that adequate information on optimum thermodynamic cycles, co ponent design and overall performance of process machinery will be available at the time lunar operations are required.

7. The long-term storage of liquid hydrogen on the lunar surface will be feasible if present development progress continues.

8. An optimum process has to be selected and work on the reliability, degree of automation, maintainability and minimum labor requirements for this process has to be carried out before a detailed cost effectiveness comparison of water produced from lunar deposits and water transported from earth for use on the moon can be made.

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DISCUSSION

VOICE: What is the present outlook for polyester film, Doctor?

DR. GLASER: If the vacuum is of the order we expect it, 10-6, they are very good.

MR. GREEN: With regard to the underground explosion, you mentioned a chimneying effect, and most of the steam escapes, and the Good Lord makes rocks so homogenous that I question the retention of a great deal of water underground.

DR. GLASER: That is indeed a problem, and I think I have some further work on Plowshares.

DR. GEORGE WU, Westinghouse: Dr. Glaser, how much energy, or what percentage of the energy was considered lost to the surface of the moon, or to the moon itself in the production of water? You indicated you were producing eight pounds of water per hour. How much of that energy was lost to the moon that did not produce water?

DR. GLASER: We assume that all of the energy that is being put into the rock is being usefully conducted to the rock. Since the energy sources would be buried probably at least a hundred feet underground, that energy could only go into the rock. And, let's say the twelve kw up to 80 kw we have been talking about would be expended in heating up the rock to the temperature needed for this dehydration to occur. Now the problem that you face is that the production rate varies as interspace between the spent rock and the fresh rock moved outward from the heat source. And I think we have presented a number of charts in this report to Cambridge Research Laboratory which would give you the further details for which you are perhaps looking.

REQUIREMENTS FOR ON-SITE MANUFACTURE OF PROPELLANT OXYGEN FROM LUNAR RAW MATERIALS

S. D. Rosenberg
G. A. Guter
M. Rothenberg

INTRODUCTION

This paper presents estimates of plant weights, power requirements, and manpower requirements for a chemical plant operating on the lunar surface. The estimates are for a plant using the Aerojet Carbothermal Process for the manufacture of propellant oxygen from lunar raw materials. For these estimates, it is assumed that no water is present in, or obtainable from, the lunar material. Many of the estimates are based on the information Aerojet has obtained as a result of research on the carbothermal process. This research is supported, in part, by NASA-OART under Contract NAS 7-225, and, in part, by Corporate funding.

A brief description of the carbothermal process is presented, followed by a detailed breakdown of each of four major process sections. Flow diagrams and summary sheets for each of these sections have been developed. Conservative estimates of all requirements have been made. Large differences in plant weights result when different cooling methods are employed. Refrigerative cooling presents an upper weight limit, while large weight savings can be realized with radiative cooling methods based upon specific assumptions. These estimates are under continuous revision at Aerojet as new data, techniques, and equipment become available.

AEROJET CARBOTHERMAL PROCESS

Process Description - Research on a chemical process for the manufacture of oxygen from lunar raw materials was initiated by Aerojet-General in 1961 and is being continued under Corporate sponsorship and NASA-OART support under Contract NAS 7-225, "Research on Processes for Utilization of Lunar Resources." The Aerojet Carbothermal Process is used to estimate plant weights in this paper; the process is represented by Equations (1) through (3).

$$MgSiO_3 + 2\ CH_4 \xrightarrow{1627^\circ C} 2\ CO + 4\ H_2 + MgO + Si \quad (1)$$

$$2\ CO + 6\ H_2 \xrightarrow{250^\circ C} 2\ CH_4 + 2\ H_2O \quad (2)$$

$$2\ H_2O \xrightarrow{75^\circ C} 2\ H_2 + O_2 \quad (3)$$

The hydrogen produced in Steps 1 and 3 is recycled to Step 2 and the methane produced in Step 2 is recycled to Step 1. The overall process is then represented by Equation (4).

$$MgSiO_3 + \text{Energy} \longrightarrow MgO + Si + O_2 \quad (4)$$

Magnesium silicate is representative of the type of lunar raw material which is probably most readily available on the lunar surface. Any water present in the silicate, either as hydrate or chemically bound as hydroxide ion, will be obtained as a by-product through simple pyrolysis in Step 1.

Investigation of all three steps of the process is now underway. Research on Steps (1) and (2) is being supported by NASA-OART under Contract NAS 7-225 (References 1 and 2). Aerojet-General is supporting work on Step (3). The estimates of the requirements which are made in this paper are based upon the best information on the process which is available to date. The flow sheet for the entire process is shown in Figure 1.

Heat Rejection - The need to reject waste heat at various locations in the plant requires a detailed study to determine the most feasible method for heat rejection. Two methods were used in this study: (1) a dual-cycle refrigeration system to "pump" the heat up to a high rejection temperature, and (2) direct heat rejection by radiation to space. The first method is based on standard refrigeration principles. It employs n-butane as the primary refrigerant with water as the secondary refrigerant, and a heat transfer medium to a space radiator. Refrigeration is not used in the second method. Instead, the assumption is made that a radiator is able to reject heat directly into 0°K space.

In the estimates for the different sections, weights and powers are given for these two different methods of cooling. In the following tables and figures, Method 1 indicates the refrigerative technique; the radiative technique is indicated by Method 2. The details of the two methods are discussed in a later section of this paper.

Reduction of Silicate with Methane - The estimates of energy requirements are based on the following changes:

$$MgSiO_{3(s)}(100°C) \longrightarrow MgSiO_{3(l)}(1627°C), \quad \Delta H = 59.62 \text{ kcal/mole} \quad (5)$$

$$CH_4(500°C) \longrightarrow CH_4(1627°C), \quad \Delta H = 21.76 \text{ kcal/mole} \quad (6)$$

$$H_2(500°C) \longrightarrow H_2(1627°C), \quad \Delta H = 8.50 \text{ kcal/mole} \quad (7)$$

$$MgSiO_{3(l)} + 2\ CH_4 \longrightarrow 2\ CO + Si + MgO + 4\ H_2, \quad \Delta H = 200.57 \text{ kcal/mole of } MgSiO_3 \quad (8)$$

The process flow sheet for this section is shown in Figure 2. Table 1 summarizes the component weights and power requirements of this section based on 90% utilization of the available oxygen.

Reduction of Carbon Monoxide with Hydrogen - The estimates of heat and power requirements are based on the following changes:

$$CO + 3\ H_2 \xrightarrow{250°C} CH_4 + H_2O, \quad \Delta H = -51.61 \text{ kcal/mole} \quad (9)$$

$$H_2\ (25°C) \longrightarrow H_2\ (250°C), \quad \Delta H = 1.58 \text{ kcal/mole} \quad (10)$$

$$CO\ (1399°C) \longrightarrow CO\ (250°C), \quad \Delta H = -9.14 \text{ kcal/mole} \quad (11)$$

$$H_2\ (1399°C) \longrightarrow H_2\ (250°C), \quad \Delta H = -8.42 \text{ kcal/mole} \quad (12)$$

$$CH_4\ (250°C) \longrightarrow CH_4\ (25°C), \quad \Delta H = -2.25 \text{ kcal/mole} \quad (13)$$

$$H_2O\ (250°C)_{(v)} \longrightarrow H_2O\ (25°C)_{(l)}, \quad \Delta H = -12.35 \text{ kcal/mole} \quad (14)$$

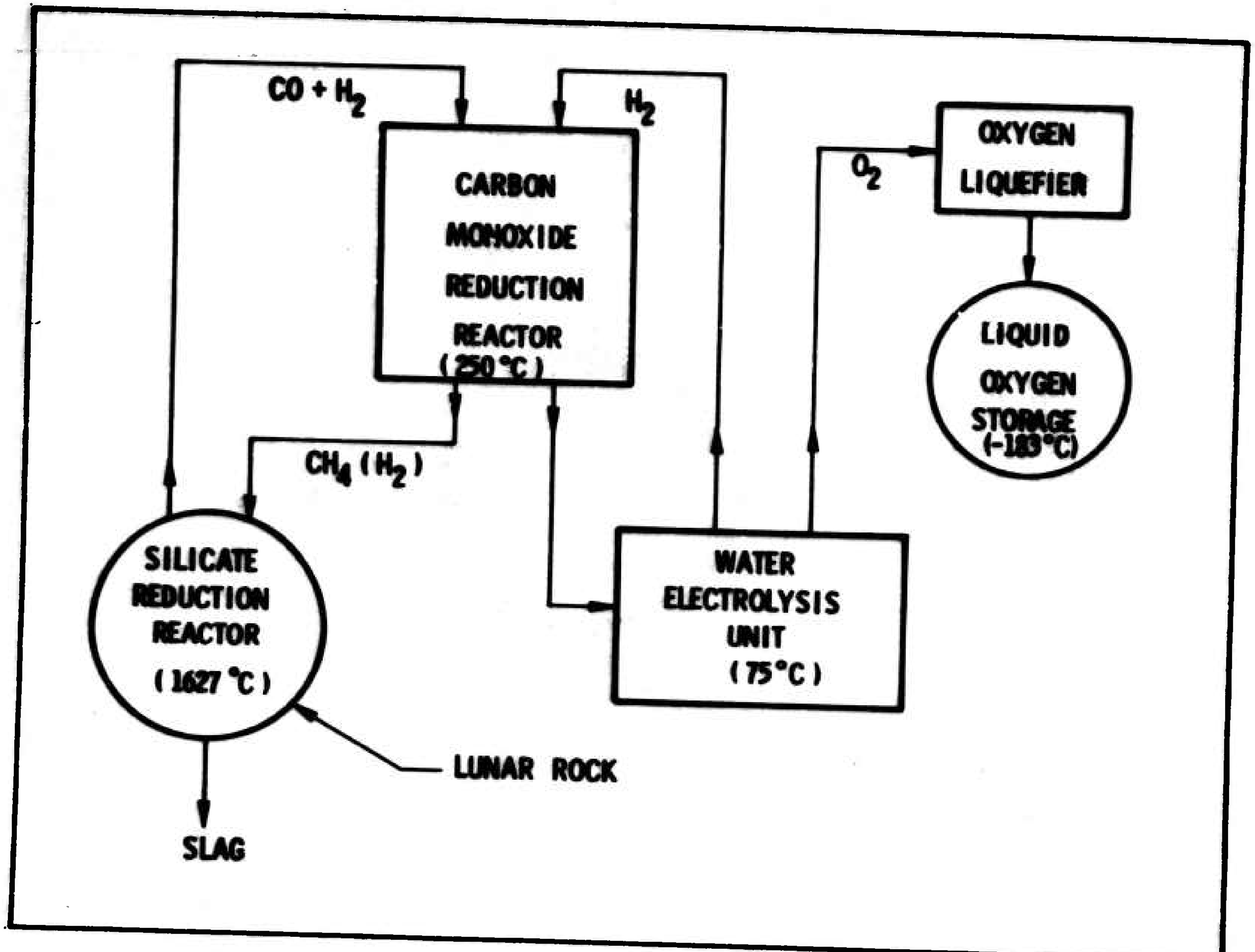


Figure 1. Simplified Flow Sheet for Aerojet Carbothermal Process

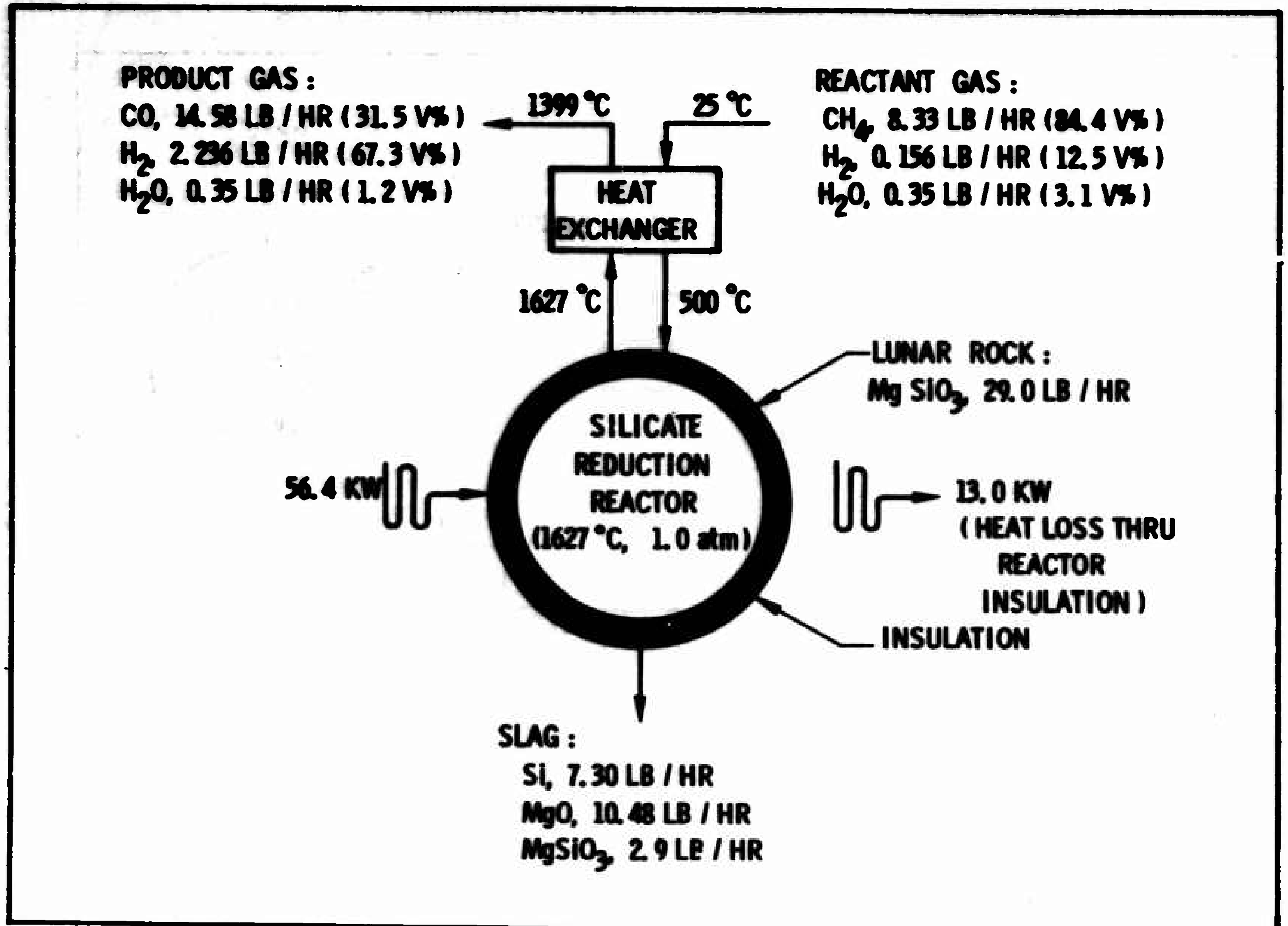


Figure 2. Silicate Reduction Reactor Section
(Based on Oxygen Production of 6000 lb/month)

TABLE 1. SILICATE REDUCTION REACTOR SECTION

Item	Plant Capacity (pounds of O_2/Earth month) 6,000	12,000	24,000
Heat exchanger to preheat CH_4 reactant gas stream with H_2-CO product gas stream	Wrap piping containing gas streams around one another, surround with reflectors, and insulate (mainly radiative-transfer)		
Area, ft^2	1.3	2.6	5.2
Weight, lb	184	232	464
Power required to heat reactants up to reactor operating temperature at startup*, kw (startup during lunar day)	16.9	33.8	67.6
Power required to heat reactants up to reactor operating temperature during steady-state*, kw (during lunar night)	15.8	31.6	63.2
Power required for reaction*, kw	27.6	55.2	110.4
Power equivalent of heat lost by radiation*, kw	13.0	18.3	26.4
Total power required to maintain reaction*, kw (maximum, based on startup)	57.5	107.3	204.4
Total power required to just maintain reaction*, kw (steady-state at night)	56.4	105.1	200.0
Size of reactor (tungsten), including insulation (graphite)	1.84 ft dia sphere, 1/4" W wall	2.15 ft dia sphere, 3/8" W wall	2.54 ft dia sphere, 1/2" W wall
Weight of reactor, empty, lb	104	246	536
Weight of insulation (4" thick), lb	345	502	734
Weight of reactor section, lb	633	980	1734
20% contingency factor, lb	126	196	346
Total estimated weight, lb	759	1,176	2,080

* Reactor operating temperature, 1627°C; reactor operating pressure, ~1 atm

The component weights and power requirements for this part of the process using Method 1 are summarized in Table 2. Table 3 summarizes the corresponding requirements using Method 2. The process flow sheet for this section is shown in Figure 3. The operating temperature of 250°C is used as a conservative value. Operating at higher temperature offers a modest advantage in reducing waste-heat radiator weight.

Water Electrolysis - The bulk of the electrolysis unit weight originates in the refrigeration cooling system and radiators used for the rejection of low-temperature heat. The details of this section are shown in Tables 4 and 5, and in Figure 4. A high-pressure electrolysis unit will allow operation at higher temperatures and higher efficiencies - a situation advantageous both for weight and for power savings. However, high-pressure electrolysis requires considerably more maintenance due to added corrosion problems and higher structural weight. Consequently, detailed trade-off analysis of low pressure vs high pressure electrolysis is required.

Oxygen Liquefaction and Storage - The oxygen liquefaction system is composed of Norelco Type 12080 gas liquefiers. These units use helium as a refrigerant; some make-up helium is required. The details of this section are shown in Tables 6 and 7, and in Figure 5. The amount of helium indicated in the tables is for a 1-year operation.

The oxygen storage system consists of 10.5-ft-OD (0.40-in.-thick wall) spheres of aluminum, each capable of containing a 6-month supply of oxygen when it is produced at a rate of 6000 lb/month. These spheres are insulated to reduce boil-off. No oxygen is lost because of boil-off as the gas is recondensed and returned to storage. The utilization of empty oxidizer storage tanks on lunar landing vehicles may eliminate the need for these storage spheres. Table 8 and Figure 5 summarize the details of this system.

Refrigeration and Heat Radiation - The flow sheet for the refrigeration system used for Method 1 cooling is shown in Figure 6. Numerical values noted apply for a heat rejection rate of 1000 Btu/hour. These values may be multiplied by the factor $\frac{Q}{1000}$ to obtain correct values at any desired heat rejection rate of Q Btu/hour.

The liquid n-butane absorbs the heat at 20°C (30 psia), vaporizes, and is compressed to 250 psia (105.5°C). The stream gives up its latent heat to liquid water at 100°C (14.7 psia) and condenses at 105.5°C (250 psia). Upon flowing through the expander, the n-butane partially flashes until its temperature and pressure are lowered to 20°C (30 psia). It is then returned to the heat exchanger where the cycle is repeated.

The water cycle operates similarly but condenses within the radiator at 204.5°C (250 psia) prior to recycle. The radiator operates continuously at this temperature. The radiators used are assumed to be stationary and to lie parallel to the lunar surface so as to be exposed to the full radiation of the overhead sun (lunar mid-day) - an extremely conservative approach.

TABLE 2. CO REDUCTION REACTOR SECTION (METHOD 1)

Item	Plant Capacity (pounds of O_2/Earth month) 6,000	12,000	24,000
Heat exchanger to heat H_2 to 250°C using silicate reduction reactor exit gas	Wrap piping containing gas streams around one another, surround with reflectors and insulate (mainly radiative transfer).		
Area, ft^2	0.3	0.6	1.2
Radiator to cool silicate reduction reactor exit gas to 250°C			
Area, ft^2	4.5	9.0	18.0
Weight, lb	18	36	72
Reactor (316 stainless steel)			
Configuration	171 tubes	342 tubes	684 tubes
	Each tube 3.21 ft long, 5/8" OD x 0.049" wall, lying horizontally to lunar surface		
Weight, lb	165	330	660
Reactor radiator (250°C)	Radiator area attached to each tube, facing upward		
Power equivalent of heat to be removed, kw	14.2	28.4	56.8
Area, ft^2	68.5	137.0	274.0
Weight, lb	86	172	344
Catalyst weight, lb	65	130	260
Radiator to cool reactor exit gas from 250°C to 100°C			
Power equivalent of heat to be removed, kw	0.8	1.6	3.2
Area, ft^2	8.8	17.6	35.2
Weight, lb	35	70	140
Refrigeration unit to cool reactor exit gas from 100°C to 25°C			
Power equivalent of heat to be removed, kw	3.3	6.6	13.2
Weight (less compressor), lb	393	786	1,572
Weight of reactor section, lb	762	1,524	3,048
20% contingency factor, lb	152	304	610
Total estimated weight, lb	914	1,828	3,658

TABLE 3. CO REDUCTION REACTOR SECTION (METHOD 2)

Item	Plant Capacity (pounds of O_2/Earth month) 6,000	12,000	24,000
Heat exchanger to heat H_2 to 250°C using silicate reduction reactor exit gas	Wrap piping containing gas streams around one another, surround with reflectors and insulate (mainly radiative transfer).		
Area, ft^2	0.3	0.6	1.2
Radiator to cool silicate reduction reactor exit gas to 250°C			
Area, ft^2	4.5	9.0	18.0
Weight, lb	18	36	72
Reactor (316 stainless steel)	171 tubes	342 tubes	684 tubes
Configuration	Each tube 3.21 ft long, 5/8" OD x 0.049" wall, lying horizontally to lunar surface		
Weight, lb	165	330	660
Reactor radiator (250°C)	Radiator area attached to each tube, facing upward		
Power equivalent of heat to be removed, kw	14.2	28.4	56.8
Area, ft^2	68.5	137.0	274.0
Weight, lb	86	172	344
Catalyst weight, lb	65	130	260
Radiator to cool reactor exit gas from 250°C to 25°C			
Power equivalent of heat to be removed, kw	4.1	8.2	16.4
Area, ft^2	88	176	352
Weight, lb	176	352	704
Weight of reactor section, lb	510	1,020	2,040
20% contingency factor, lb	102	204	408
Total estimated weight, lb	612	1,224	2,448

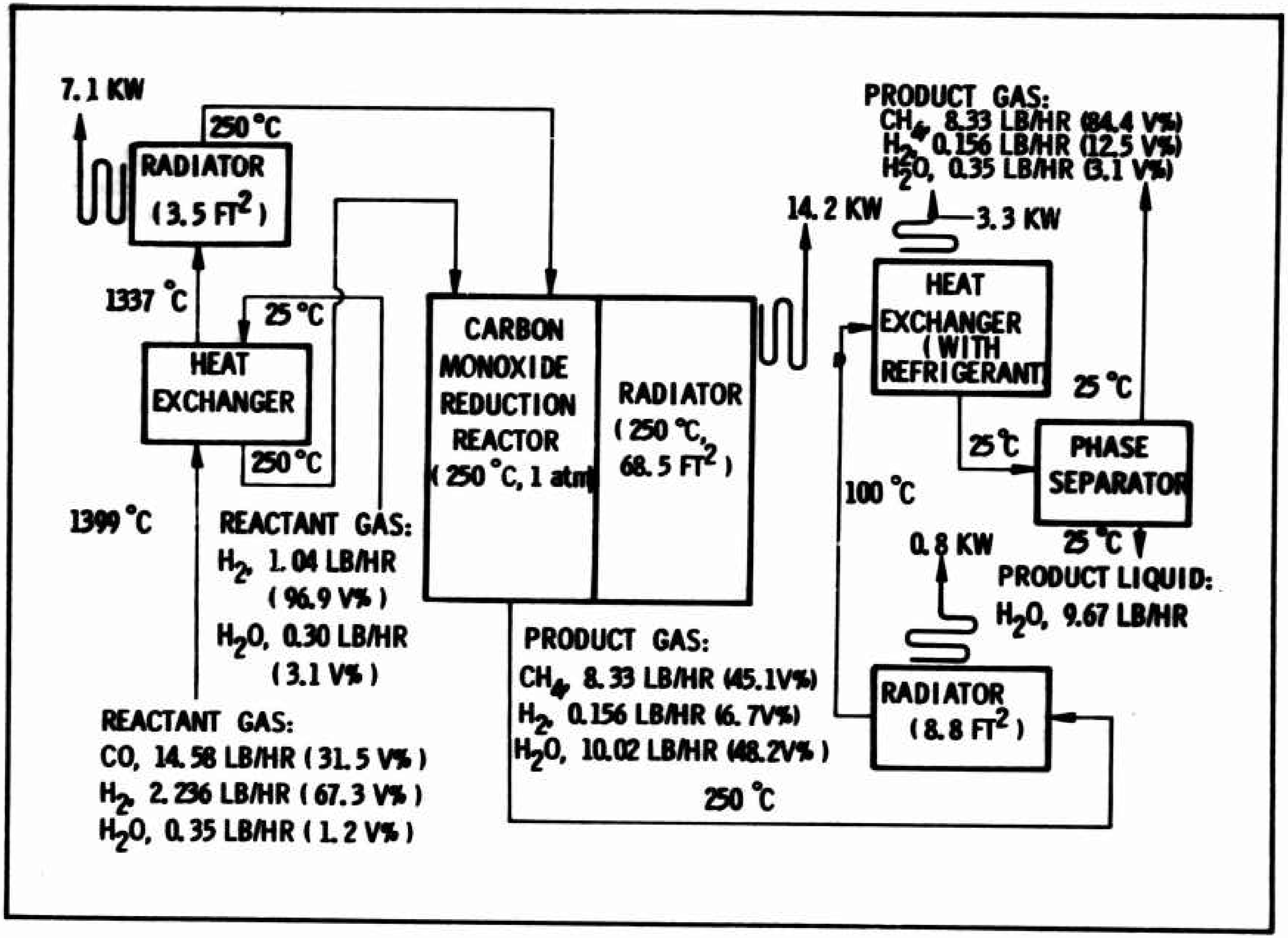


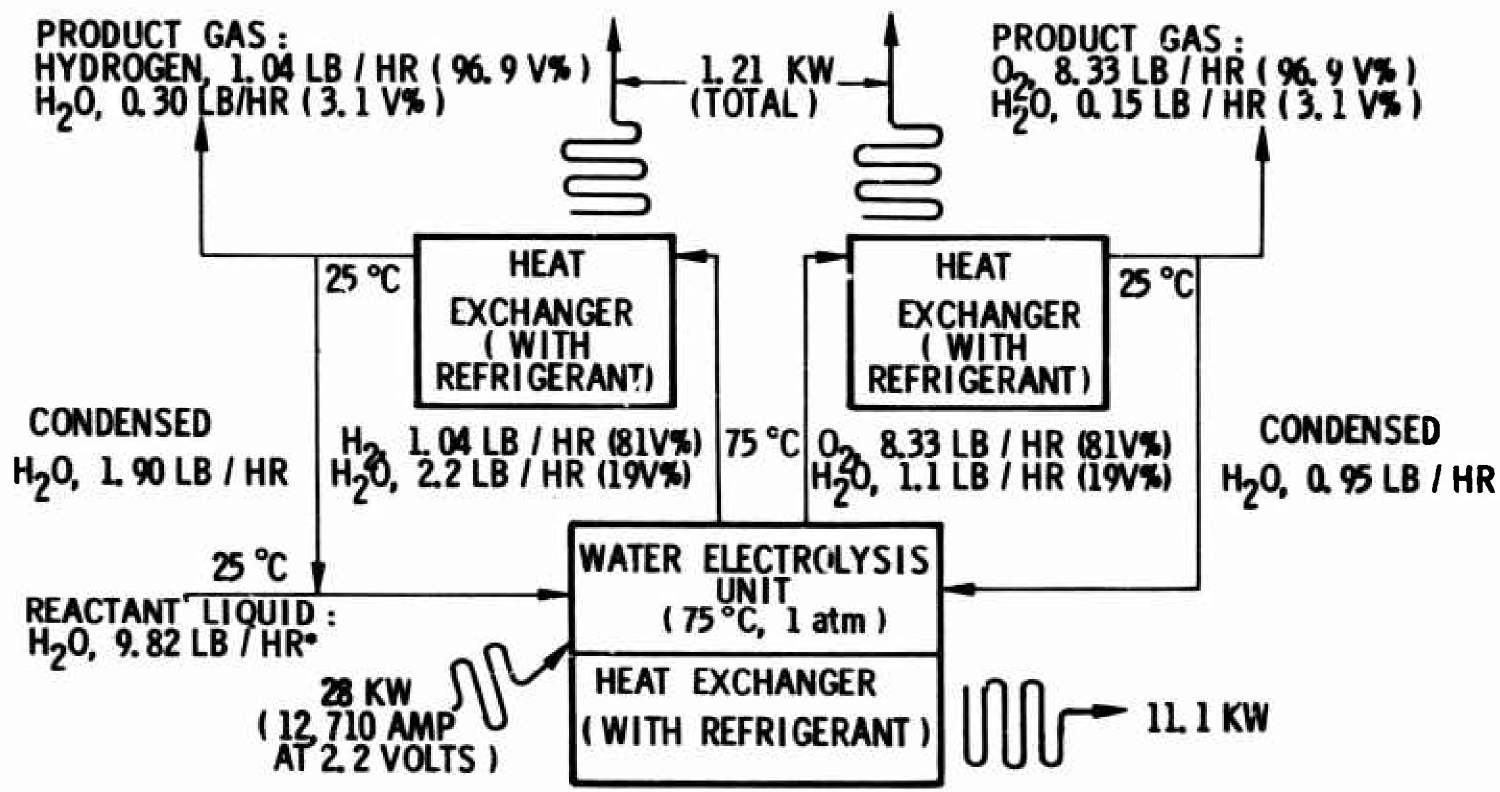
Figure 3. Carbon Monoxide Reduction Reactor Section (Based on Oxygen Production of 6000 lb/month)

TABLE 4. WATER ELECTROLYSIS SECTION (METHOD 1)

Item	Plant Capacity (pounds of O_2/Earth month) 6,000	12,000	24,000
Electrolytic Cell (75°C, 1 atm)			
Dimensions	15.5" long x 26" wide x 28" high	30.5" long x 26" wide x 28" high	60.5" long x 26" wide x 28" high
Construction	Alternate anodes and cathodes separated by polyethylene spacers and gaskets, as needed.		
Electrode weight, lb	63.5	93.5	154.0
Spacer assembly weight, lb	15.3	30.6	61.2
Diaphragm weight, lb	0.9	1.8	3.6
Cell weight (dry), lb	79.7	125.9	218.8
Potassium hydroxide weight (for 28% solution), lb	43.5	87.0	174.0
Operating voltage, volts	2.2	2.2	2.2
Operating current, amps	12,710	25,420	50,840
Power requirement, kw	28	56	112
Refrigeration unit to cool exit gas from 75°C to 25°C			
Power equivalent of heat to be removed, kw	1.2	2.4	4.8
Weight (less compressor), lb	149	300	600
Refrigeration unit to maintain cell at 75°C			
Power equivalent of heat to be removed, kw	11.1	22.2	44.4
Weight (less compressor), lb	1,294	2,589	5,177
Weight of electrolysis section, lb	1,567	3,102	6,170
20% contingency factor, lb	314	620	1,234
Total estimated weight, lb	1,881	3,722	7.404

TABLE 5. WATER ELECTROLYSIS SECTION (METHOD 2)

Item	Plant Capacity (pounds of O_2/Earth month) 6,000	12,000	24,000
Electrolytic Cell (75°C, 1 atm)			
Dimensions	15.5" long x 26" wide x 28" high	30.5" long x 26" wide x 28" high	60.5" long x 26" wide x 28" high
Construction	Alternate anodes and cathodes separated by polyethylene spacers and gaskets, as needed.		
Electrode weight, lb	63.5	93.5	154.0
Spacer assembly weight, lb	15.3	30.6	61.2
Diaphragm weight, lb	0.9	1.8	3.6
Cell weight (dry), lb	79.7	125.9	218.8
Potassium hydroxide weight (for 28% solution), lb	43.5	87.0	174.0
Operating voltage, volts	2.2	2.2	2.2
Operating current, amps	12,710	25,420	50,840
Power requirement, kw	28	56	112
Radiator to cool exit gas from 75°C to 25°C			
Power equivalent of heat to be removed, kw	1.2	2.4	4.8
Area, ft^2	53	106	212
Weight, lb	106	212	424
Radiator to maintain cell at 75°C			
Power equivalent of heat to be removed, kw	11.1	22.2	44.4
Area, ft^2	286	572	1144
Weight, lb	572	1,144	2,288
Weight of electrolysis section, lb	802	1,569	3,105
20% contingency factor, lb	160	314	622
Total estimated weight, lb	962	1,883	3,727



* 9.37 LB / HR REQUIRED FOR ELECTROLYSIS

0.30 LB / HR RECYCLED WITH HYDROGEN STEAM

0.15 LB / HR CONDENSED IN LIQUID OXYGEN COLD TRAP AND RETURNED TO ELECTROLYSIS UNIT INTERMITTENTLY

Figure 4. Water Electrolysis Section
(Based on Oxygen Production of 6000 lb/month)

TABLE 6. OXYGEN LIQUEFACTION SECTION (METHOD 1)

Item	Plant Capacity (pounds of O_2/Earth month)		
	6,000	12,000	24,000
Rate of O_2 condensation, liquid quarts/hour	3.5	7.0	14.0
Norelco Type 12080 gas liquefier			
Dimensions, inches	Approximately 37 long x 20 wide x 34 high		
Capacity	5 quarts of liquid air per hour		
Number of units required	2 (one operating, one spare)	3 (two operating, one spare)	4 (three operating, one spare)
Weight of units, lb	1,320	1,980	2,640
Power required at 200 V AC (maximum), kw	7.46	14.92	22.38
Helium weight (for 1-year operation, includes containers), lb	242	484	726
Refrigeration unit to remove heat from liquefier			
Power equivalent of heat to be removed, kw	7.9	15.8	23.7
Weight (less compressor), lb	1,069	2,137	3,206
Weight of oxygen liquefaction section, lb	2,631	4,601	6,572
20% contingency factor, lb	526	920	1,314
Total weight, lb	3,157	5,521	7,886

TABLE 7. OXYGEN LIQUEFACTION SECTION (METHOD 2)

Item	Plant Capacity (pounds of O_2/Earth month) 6,000	12,000	24,000
Rate of O_2 condensation, liquid quarts/hour	3.5	7.0	14.0
Norelco Type 12080 gas liquefier			
Dimensions, inches	Approximately 37 long x 20 wide x 34 high		
Capacity	5 quarts of liquid air per hour		
Number of units required	2 (one operating, one spare)	3 (two operating, one spare)	4 (three operating, one spare)
Weight of units, lb	1,320	1,980	2,640
Power required at 200 V AC (maximum), kw	7.46	14.92	22.38
Helium weight (for 1-year operation, includes containers), lb	242	484	726
Radiator to maintain units at 30°C			
Power equivalent of heat to be removed, kw	7.9	15.8	23.7
Area, ft^2	437.5	875.0	1312.5
Weight, lb	875	1,750	2,625
Weight of oxygen liquefaction section, lb	2,437	4,214	5,991
20% contingency factor, lb	488	842	1,198
Total estimated weight, lb	2,925	5,056	7,189

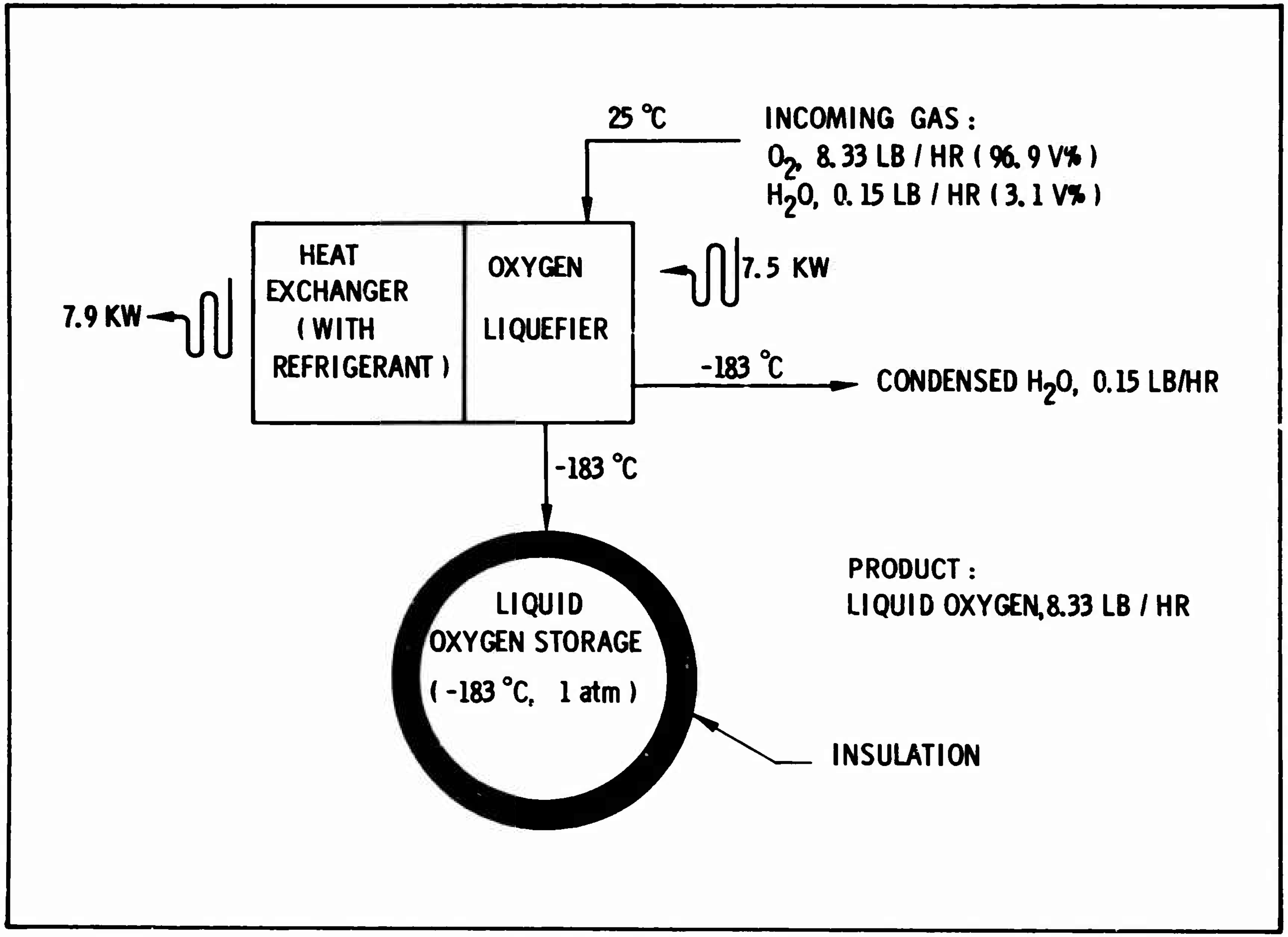


Figure 5. Oxygen Liquefaction and Storage Section
(Based on Oxygen Production of 6000 lb/month)

TABLE 8. OXYGEN STORAGE SECTION

Item	Plant Capacity (pounds of O_2/Earth month)		
	6,000	12,000	24,000
O_2 Storage-holding 6 months supply			
Shape	1-10.5 ft OD sphere 0.40" thick shell	2-10.5 ft OD spheres 0.40" thick shell	4-10.5 ft OD spheres 0.40" thick shell
Weight (aluminum), lb	1,975	3,950	7,900
Insulation	1" thickness, AGC-Multilayer Insulation, Type 101		
Weight, lb	375	750	1,500
Weight of storage section, lb	2,350	4,700	9,400
10% contingency factor, lb	235	470	940
Total estimated weight, lb	2,585	5,170	10,340

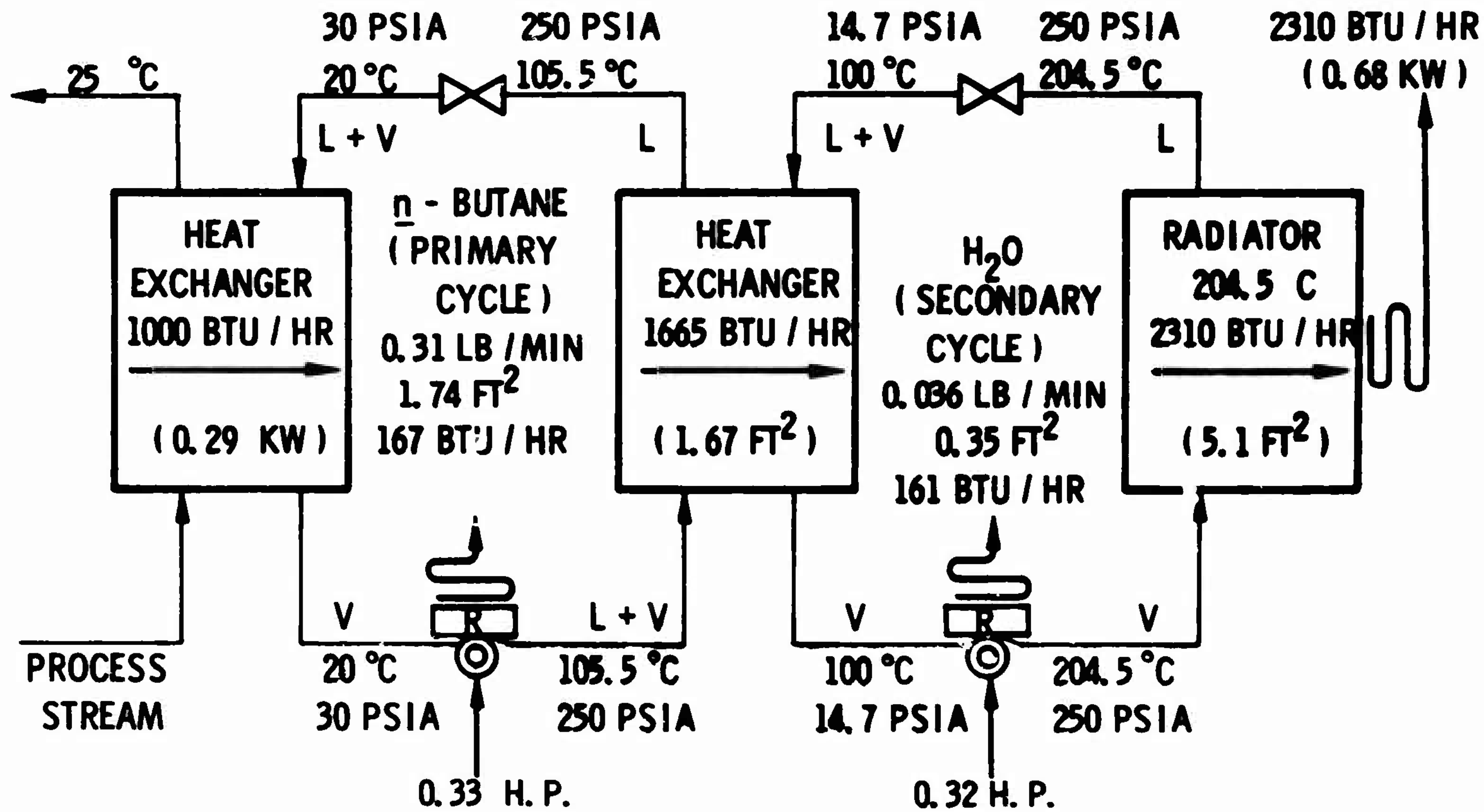


Figure 6. Dual Cycle Refrigerative Cooling Method (Based on Heat Removal of 1000 BTU/Hr)

The radiator material is assumed to have an absorptivity of 0.35 and an emissivity of 0.77. The heat rejection rates for this type of radiator are taken from Reference 3. The reported values are lowered to allow for an estimated 80% efficiency. The radiator weight factors used in our estimates were 1.25 lb/ft^2 surface area for a plain radiator, and 4.0 lb/ft^2 surface area for a radiator with refrigeration. This latter value was also used for systems in which fluids condense or cool in tubes within or attached to the radiator. The 4.0 weight factor was obtained from Reference 3.

Compressor efficiencies are taken as 80%. The extra power required is rejected as heat from radiators attached to the compressors. Weights of standard compressor and motor units selected for use here were reduced by assuming that non-electrical parts could be fabricated from lightweight aluminum alloys.

Refrigeration is not needed in Method 2. The assumption is made that the radiator sees 0°K space either by being perpetually shadowed (e.g., when located in depressions near the poles), or by being movable so as to present only an edge to the direct rays of the Sun. An iron-clad aluminum radiator would provide an emissivity of about 0.5 in a lightweight body. Reflectors on its underside and edge would prevent pickup of most of the radiation from the Moon's surface and from the Sun. The weight factor is taken as 2 lb/ft^2 surface. Once again, an 80% efficiency factor was used.

Total System Weight and Power - Table 9 lists the total system weights and power requirements for the three lunar oxygen plants, using Method 1 (refrigerative cooling). Table 10 does the same for Method 2 (radiative cooling). The differences in weight and power requirements for the two methods are striking, indicating that heat rejection techniques are of major importance in lunar plant design. In either case, scaling factors remain about constant.

In summary, this study indicates that a lunar oxygen plant with a production capacity of 6000 lb of oxygen per month, and based on the Aerojet Carbothermal Process, would weigh approximately 10,275 lb and require 132 kwe using refrigeration cooling; a similar plant using radiative cooling exclusively would weigh approximately 7850 lb and require 93 kwe. All estimates are based on a conservative approach to the problem at hand.

MANPOWER ESTIMATES

It is estimated that a maximum of one-third of a man-day will be required for plant operation and maintenance for each 24 hours of plant operation for each of the three plants under study. One month of plant operation will require 240 man-hours of labor. Based on a cost of $100,000 per man-hour, the labor cost for the manufacture of 1 lb of oxygen using the 6000-, 12,000-, and 24,000-lb capacity plants are $4000, $2000, and $1000, respectively.

TABLE 9. LUNAR OXYGEN PLANT WEIGHT AND POWER REQUIREMENTS (METHOD 1)

Section	Plant Capacity (pounds of O_2/Earth month) 6,000	12,000	24,000
Silicate Reduction Reactor, lb	759	1,176	2,080
Carbon Monoxide Reduction Reactor, lb	914	1,828	3,658
Water Electrolysis Unit, lb	1,881	3,722	7,404
Oxygen Liquefaction, lb	3,157	5,521	7,886
Refrigeration Compressors, lb	980	1,740	3,100
Sub-Total Weight, lb	7,691	13,987	24,128
Liquid Oxygen Storage, lb	2,585	5,170	10,340
Total Weight, lb	10,276	19,157	34,468
Silicate Reduction Reactor, kw	57.5	107.3	204.4
Water Electrolysis Unit, kw	28.0	56.0	112.0
Oxygen Liquefaction, kw	7.5	15.0	22.5
Refrigeration Compressors, kw	38.4	76.8	140.9
Total Power, kw	131.4	255.1	479.8

TABLE 10. LUNAR OXYGEN PLANT WEIGHT AND POWER REQUIREMENTS (METHOD 2)

Section	Plant Capacity (pounds of O_2/Earth month) 6,000	12,000	24,000
Silicate Reduction Reactor, lb	759	1,176	2,080
Carbon Monoxide Reduction Reactor, lb	612	1,224	2,448
Water Electrolysis Unit, lb	960	1,883	3,727
Oxygen Liquefaction, lb	2,925	5,056	7,189
Sub-Total Weight, lb	5,256	9,339	15,444
Liquid Oxygen Storage, lb	2,585	5,170	10,340
Total Weight, lb	7,841	14,509	25,784
Silicate Reduction Reactor, kw	57.5	107.3	204.4
Water Electrolysis Unit, kw	28.0	56.0	112.0
Oxygen Liquefaction, kw	7.5	15.0	22.5
	93.0	178.3	338.9

TABLE 11. COST COMPARISON OF EARTH-MOON OXYGEN TRANSPORT VS LUNAR OXYGEN MANUFACTURE (ONE YEAR COST SAVINGS)

Plant Capacity, lb O_2/Earth month	6,000	12,000	24,000
Pounds of O_2 Per Year	72,000	144,000	288,000
\$Cost of Delivered O_2[1]	360×10^5	720×10^6	$1,440 \times 10^6$
\$Cost of Plant Delivery[1,3]	51×10^5	96×10^6	172×10^6
\$Cost of Labor[2]	291×10^6	291×10^6	291×10^6
\$Saved by Lunar O_2 Plant[3]	18×10^6	333×10^6	977×10^6
\$Saved by Lighter Lunar O_2 Plant[4]	30×10^6	356×10^6	$1,035 \times 10^6$

1 Delivery cost of \$5,000 per pound

2 Labor cost of \$100,000 per man-hour for 1/3 year

3 Refrigerative cooling, Method 1

4 Radiative cooling, Method 2

COST COMPARISONS

The dollar costs for the manufacture of oxygen on the Moon can be compared with the cost of delivering oxygen from the Earth by using a cost of $5000 per pound of payload and a labor cost of $100,000 per man-hour. The cost comparison is given in Table 11. Thus, the manufacture of 6,000 lb of oxygen per month for 1 year would cost $342 million (Method 1, most conservative estimate) while the transport of an equivalent amount of oxygen would cost $360 million.

Larger savings would be realized if the cost of oxygen storage on the Moon were considered. In contrast to manufactured oxygen, the transport cost of oxygen does not include the cost of lunar storage. Similarly, the utilization of lunar landing vehicle propellant tanks for storage will reduce the cost of manufactured oxygen while the cost of transport oxygen will remain the same.

The data reported in Table 11 dramatically indicates that much greater dollar savings will be realized by the manufacture of propellant oxygen on the Moon as the oxygen requirements are increased above 6000 lb per month.

REFERENCES

1. S. D. Rosenberg, G. A. Guter, F. E. Miller, and G. R. Jameson, Research on Processes for Utilization of Lunar Resources, Aerojet-General Summary Report No. 2757, Contract NAS 7-225 (December 1963).

2. S. D. Rosenberg, G. A. Guter, and F. E. Miller, Research on Processes for Utilization of Lunar Resources, Aerojet-General Summary Report No. 2895, Contract NAS 7-225 (August 1964).

3. Lunar Logistic Systems, Vol. X, Payloads. George C. Marshall Space Flight Center Report MTP-M-63-1 (March 1963).

DISCUSSION

QUESTION: In your talk I did not get whether or not your power cost figure had been cranked into that?

DR. ROSENBERG: No. As I said, this is a turnkey package. So we have not considered the weight, or the cost or the problems of delivering what I would call a nuclear electric power plant. We have not considered that, but another group in the committee in the subgroup will be doing that. So eventually we will be able to come together on that problem.

MR. GREEN: I take it you are going to process 29 pounds of rock per hour which will take 8-1/3 pounds of methane per hour?

DR. ROSENBERG: Right.

MR. GREEN: You are going to deliver it, is that right?

DR. ROSENBERG: Yes. The weights here include the initial weight of the methane.

MR. GREEN: What about make up?

DR. ROSENBERG: Well, no make up. We will hope that we will approach perfection, which we will not, but a plant this size presupposes a rather substantial carbon generating plant on the moon, namely man himself. We have got a pretty good garbage dump here. And would be glad to have the carbon, but not the sulphur. But you are right, one of the logistic requirements of this plant will be methane, in modest amounts.

MR. GREEN: What about replacement?

DR. ROSENBERG: No, the methane is recycled. It is just make up, and the more clever we are in the design the less dependent we will become. But this is not a one-charge methane run-through, because the whole plant is based on recycling.

MR. THOMPSON: In the carbon monoxide production process you showed that it is catalyzed?

DR. ROSENBERG: Definitely. Catalyzed reactions very similar to Sebatier.

SOME USES FOR PLANETOID RESOURCES

D. M. Cole

We have been hearing quite a lot about the moon - perhaps ninety percent of the work of the Working Group has been on the moon. Dr. Steinhoff mentioned yesterday that there were, after all, other places in the Solar System, and as you know Dr. Steinhoff himself has studied the possible use of resources on Mars and the Moons of Mars.

I want to look at something different today, which I think might be of particular interest to the Working Group. In one way my remarks will be quite similar to those of Jack Green this morning, in that he was asking you questions; I will ask similar questions about what kind of resources we want the most, where we are likely to find them. However, I will take a broader look at the whole Solar System, rather than just the moon.

Now what objects in the Solar System would be of interest to us? That depends of course on who we are; if we are astronomers, then we have one sort of interest - if we are looking through telescopes; if we are people sending out rocket probes, we might have another interest - another attitude toward what is interesting in the Solar System, we would have still another set of attitudes toward what is interesting and what is feasible, and I think the Working Group on Extra Terrestrial Resources has still another attitude toward what is interesting and feasible. I have tried to list here my own opinion as to the interesting objects in the Inner Solar System as to degree of interest (Figure 1). These are ordered on a basis of feasibility, accessibility and desirability, and I think that this ordering would be applicable both to the explorer and to the Working Group to try to come up with such a list. We hear so much about the Moon, Mars and Venus, and they are not necessarily the most interesting space objects to a group like this.

Although this was done in a very qualitative way - this weighting and ordering - quite a study could be made of trying to make such a list. Note in order the Moon close approach planetoids, Moons of Mars, the Planetoid Belt, and Number Five is Mars.

Now between four and five, we have a practical division. The first four are things that we can do something about in terms of manned space flight with extension of the Apollo Program, with Saturn V and with the technology being built up for the Apollo Program.

Now many people feel that to land on Mars we need nuclear rockets and if that is true, we have a propulsion system division there between numbers four and five. In any case, I heard on television a couple of days before I came down here that somebody was talking about the Moon of Jupiter as the next thing to look at after Mars, and I think their order of interest was the Moon, Mars and then the Moons of Jupiter. I don't know who that was, but there are some other things which perhaps should get prior consideration to the Moons of Jupiter.

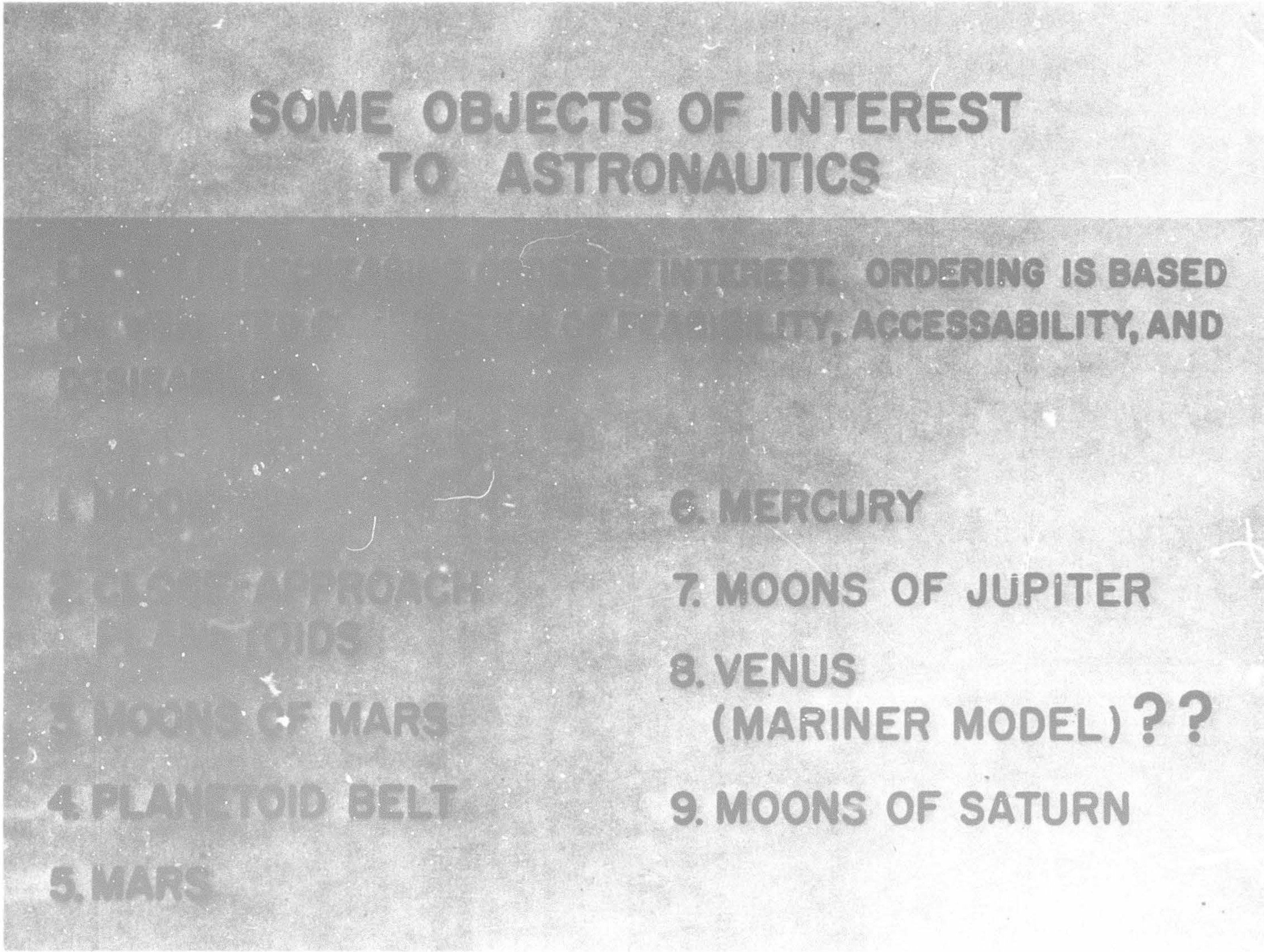

SOME OBJECTS OF INTEREST
TO ASTRONAUTICS
ORDERING IS BASED
ACCESSABILITY, AND
3. MOONS OF MARS
4. PLANETOID BELT
5. MARS
6. MERCURY
7. MOONS OF JUPITER
8. VENUS
(MARINER MODEL) ??
9. MOONS OF SATURN

Figure 1

Mercury, for one, should come ahead of the Moons of Jupiter in terms of feasibility of getting there; it is a much easier job and it takes a lot shorter time. Particularly since Kosyrev has found that it has a hydrogen atmosphere. We might even be able to use the atmosphere of Mercury for atmospheric braking, which reduces the total velocity requirements for the round trip very considerably.

Now where should we put Venus in the list? This depends on what model of Venus we take. If we take the Mariner model, then it doesn't appear to be a very interesting place to go for any explorers or for members of the Working Group who want to make use of resources.

Figure 2 shows some of the basis for this ordering of space objects. And here we get a little difference between the explorer and the exploiter. I don't know whether we want to call ourselves exploiters or not in this group, but maybe that is what we are. We want to use things, anyway.

Now the explorer is interested in the velocity requirements that he needs, velocity changes that he has to go through to get to the destination and back again. The exploiter, if he wants to use materials from this space object and particularly if he wants to use it somewhere else, may be interested in a different set of velocity requirements. In particular, I think the most useful extra-terrestrial resource that we could possibly get hold of would be rocket propellants that we could return to low earth orbit. If we could have a source of rocket propellants at low earth orbit, we could reduce costs and change the entire picture of space flight logistics. So, if we use that as a criteria, how can we get rocket propellants back to low earth orbit? And how hard is it to get the payloads back from various places in the Solar System? We get the sort of a list shown in Figure 2, velocity in feet per second required to go from the various places back to low earth orbit. From the earth's surface it is 30,000 feet a second; from the moon 9000, and this object of which we will hear more later, Wilson-Harrington, is only 1,000. Eros is 2,000, the Moons of Mars 7,000, Mars itself 20,000, and the planetoids out in the belt between Mars and Jupiter, some of them about 3,000, if they have low inclinations to the plane of the ecliptic. If you look at the relative energy involved, which is a much better measure of difficulty than the velocity, you see an enormous difference between, for example, Wilson-Harrington and the earth's surface.

Note that for the Moon compared to the earth's surface, you have a factor of about ten in energy. That looks as though it would be a good idea to bring propellants from the Moon back to low earth orbit. Actually it might be if we had a good enough technique for doing it. However, using the kind of rockets we have now and factoring in all the hardware you must take to the moon to generate the propellants, this is a very marginal proposition. If we have some very futuristic device like the electric catapult that Arthur Clarke suggested for firing projectiles back from the Moon to low earth orbit, then that might become a pretty good source.

The Moons of Mars are a little better source in terms of energy than the Moon. Mars itself does not look good at all, it is almost as bad as the earth. The belt planetoids look pretty good. Eros looks very good, and Wilson-Harrington looks perfect.

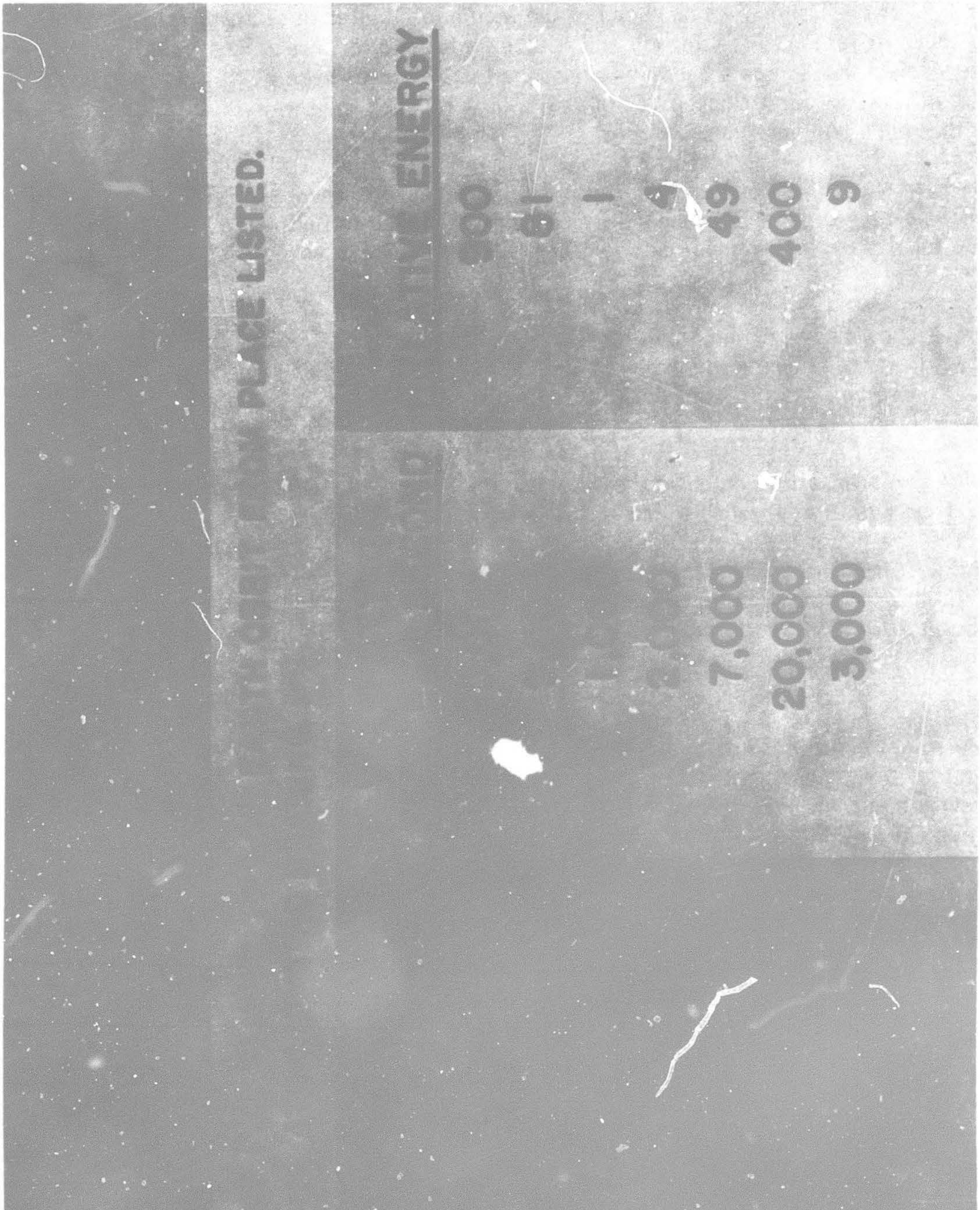


Figure 2

The next question concerns the kind of materials we might find on these planetoids and so we have, in Figure 3, a table of probable composition. On the left we have the major components in the compounds, and on the right we have the trace elements.

Now how can we have such a table when nobody has been there? Well, of course, we don't really know that this is the way things are on the planetoids, but this is perhaps the best guess we can make right now. This table is actually from Middlehurst and Kuipers' book, "The Moon, Meteorites and Comets." It is from the chapter by J. E. Wood, and this is the composition of the ordinary chondrites, which as most of you know constitute 75 percent of all the meteorite falls. You remember that about half of all the meteorites are those seen to fall, and the other half are called the finds. The finds are almost all irons, whereas the falls are 93 percent stones. And, of the falls, 75 percent are the ordinary chondrites. Note one very significant item down near the bottom. Water approximately three-tenths of one percent for the ordinary chondrites. Now the carbonacious chondrites, you may know, run very much higher, some ten to twenty percent water.

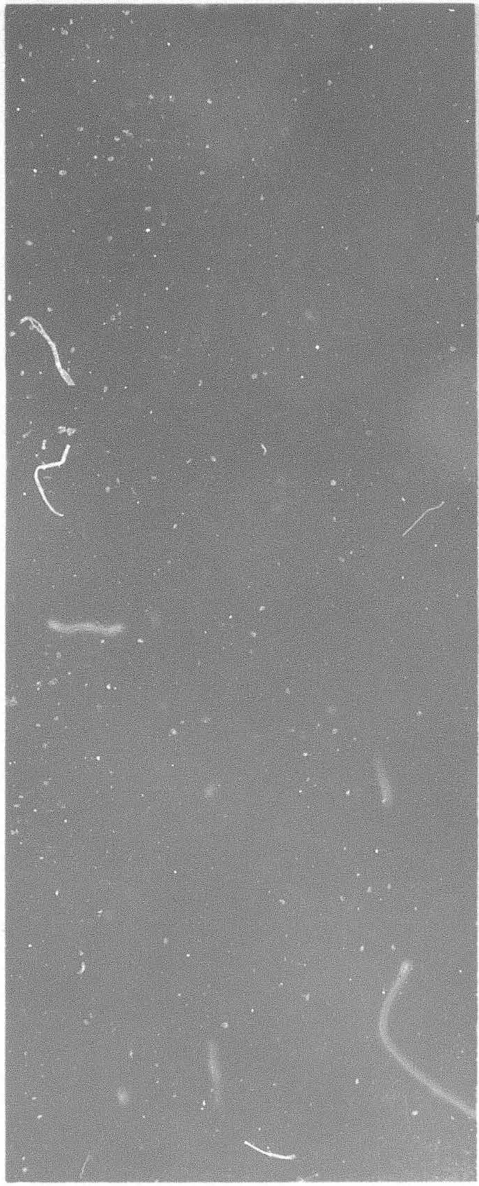
Another interesting point is that we would have some hydrogen there, we would have oxygen, and almost everything else we might want for setting up a base on a planetoid, but there is one item that might cause some embarrassment, and that is nitrogen. Only ninety parts per million - only ninety atoms of nitrogen for every million of silicate. To provide for growth of our base or for a colony on the planetoid, we would have to have some source of nitrogen.

Perhaps I should have started with Figure 4, but I assumed that everybody in this room carries a little picture like this around in his head, anyway, and so we don't have to go over the geography of the Solar System. I do want to point out one of these bodies, Eros, which comes in close to the orbit of the earth but does not cross it.

And Geographos, another typical close approach object, which actually crosses the orbit of the Earth and goes inside almost to the orbit of Venus. Now we will have to try to remember those orbits as we go on to Figure 5.

We have again Geographos and Eros, and a couple of other interesting ones - Icarus that goes inside the orbit of Mercury, and of course Ceres representative of the belt asteroids out beyond Mars, and Betulia which we will mention in a minute again. I think those are enough to have a feel for what all these things are.

There are a couple of interesting points about Figure 6 and also a change. On the left we have the condition of the orbit of the most important close approach asteroids. The upper ones are in good condition. That is we are pretty sure of finding them on every return. The next lower group were considered doubtful, and the lower group have been considered lost. Just three years ago there were only four of these, Eros, Icarus, Betulia and Geographos with good orbits. In 1962 Ivar was recovered and this year Amor was recovered.



COMPONENT	%	ELEMENT	CONCENTRATION ATOMS/10^6 Si ATOMS	ELEMENT	CONCENTRATION ATOMS/10^6 Si ATOMS
SiO_2	38.29	He	0.11	Nb	1
MgO	23.93	Li	50	Mo	2.5
FeO	11.95	Be	0.64	Ru	1.6
Al_2O_3	2.72	B	40	Rh	0.27
CaO	1.90	C	{20,000 {2000	Pd	1.1
Na_2O	0.90	N	90	Ag	0.13
K_2O	0.10	F	300	Cd	0.064
Cr_2O_3	0.37	Ne	0.0015	In	0.0013
MnO	0.26	Cl	1000	Sn	1.1
TiO_2	0.11	A	0.4	Sb	0.1
P_2O_5	0.20	Sc	30	Te	1
H_2O	0.27	V	160	I	0.05
FeS	5.89		900	Xe	0.000007
TOTAL SILICATES	81.00	Co	1200	Cs	0.12
TOTAL METALS	13.11	Cu	190	Ba	4.0
		Zn	120	La	0.4
		Ga	12	Ce	1.1
		Ge	19	Pr	0.2
		As	4.7	Nd	0.8
		Se	17	Sm	0.3
		Br	{32 {2	Eu	0.1
		Rb	7	Gd	0.4
		Sr	20	Tb	0.06
		Y	3.6	Dy	0.3
		Zr	65	Ho	0.08
				Er	0.2
				Tm	0.04
				Yb	0.2

Figure 3

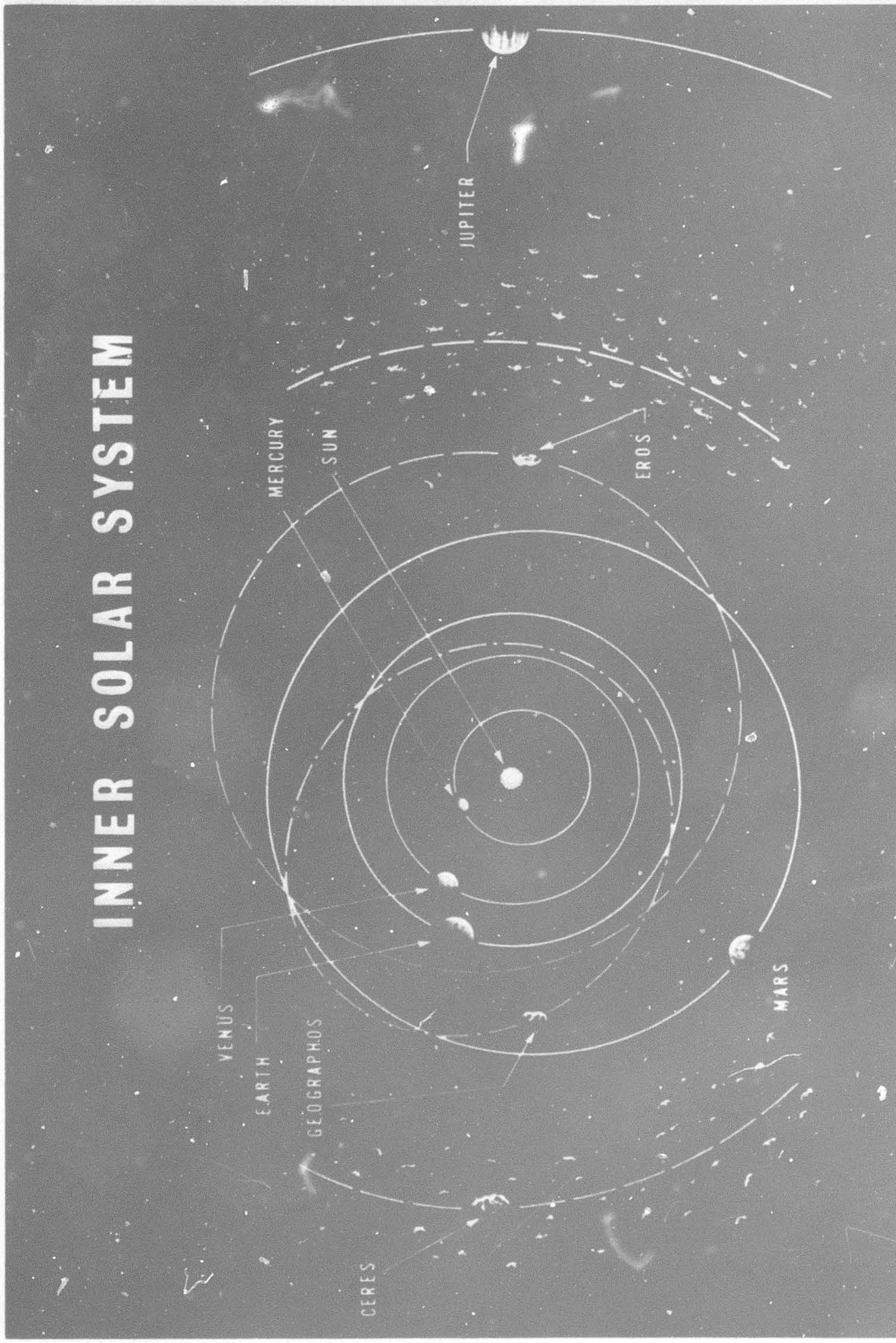

INNER SOLAR SYSTEM
JUPITER
MERCURY
SUN
EROS
VENUS
EARTH
GEOGRAPHOS
MARS
CERES

Figure 4

CLOSE-APPROACH PLANETOID ORBITS

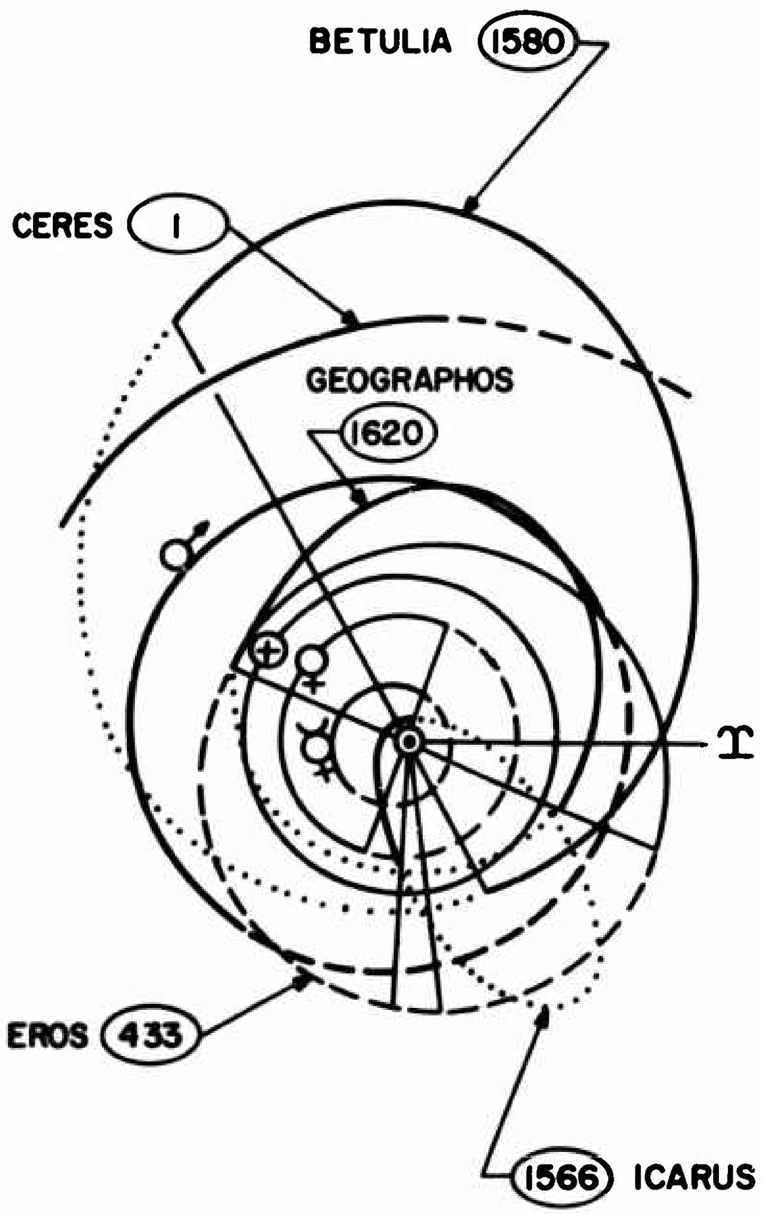


Figure 5

Condition of Orbit	No.	Name	t_o	M_o °	ω °	Ω °	i °	e = sinϕ	n sec	a AU	R_p AU	R_A AU	Close Approach to Earth	Diameter Miles	P Yr.
Good	433	Eros	1931 Jan. 16	0.568	177.930	304.071	10.831	0.2230	2015.293	1.4581	1.1064	1.8073	0.15 (1967) (1975)	15	1.761
	1221	Amor	1948 June 3	22.165	25.649	171.202	11.934	0.4366	1234.746	1.9199	1.0850	2.7530	0.115 (1964) (1972)		2.656
	1566	Icarus	1959 Aug. 7	53.480	30.912	87.746	22.979	0.8266	3171.432	1.0777	0.1869	1.9685	0.042 (1968)		1.119
	1580	Betulia	1962 Dec. 14	291.862	156.868	61.874	52.037	0.4926	1090.783	2.1954	1.1135	3.2773	0.156 (1963) (1976)		3.253
	1620	Geographos	1954 Dec. 26	196.077	276.211	336.980	13.325	0.3352	2556.94	1.2441	0.8271	1.6611	0.073 (1969)	1	1.388
	1937NA	Ivar	1937 July 1	253.558	166.963	132.851	8.430	0.3960	1394.004	1.8642	1.138	2.59	0.14 (1962) (1967) (1972)	3	2.53
Doubtful	719	Albert	1911 Oct. 3	7.929	151.940	186.004	10.828	0.5406	853.665	2.5852	1.1876	3.9828	0.188	2-3	4.157
	887	Alinda	1942 Jan. 31	358.049	349.119	111.029	9.024	0.5398	886.351	2.5212	1.1602	3.8822	0.16		4.003
		1948 OA	1948 Oct. 7	0.000	126.314	274.191	9.397	0.4360	2217.81	1.3679	0.7715	1.9643	0.07		1.600
Lost		Apollo	1932 Apr. 28	319.984	284.878	36.977	6.422	0.5663	1958.60	1.4861	0.6445	2.3277	0.0699 (1932)	1-2	1.812
		Adonis	1936 Feb. 26	32.686	39.537	352.538	1.480	0.7792	1284.03	1.9692	0.4348	3.5036	0.0161 (1936)	1-2	2.763
		Hermes	1937 Nov. 7	327.036	90.687	35.367	4.685	0.4746	2420.68	1.2904	0.6780	1.9028	0.0052 (1937)	< 1	1.468
	1949 III	Wilson-Harrington	1949 Oct. 13		91.95	278.64	2.20	.4122		1.75	1.0276	2.47	.028	3.6	2.31

Explanation of symbols: t_o = Epoch, M_o = Mean anomaly at epoch t_o, ω = Argument of the perihelion, Ω = Longitude of the ascending node, i = inclination of orbital plane to ecliptic, e = Eccentricity, n = Mean daily motion, a = Major semi-axis, R_p, R_A = Perihelion and aphelion distance, P = period of revolution. Unit of col. 13 is AU

Figure 6

Now the change in the table. Some of you may want to write it in. Dr. Sam Herrick has recently announced that 1948 OA is now in good shape and he has given it the maiden name of his wife, Toro; Betulia, as you know, is the first name of his wife, and she is the only person, I believe, who has two planetoids named after her.

Now this is an interesting point, that we have two of these recovered this year. According to Sam Herrick's group out at the University of California, there are two more that are not listed on here at all, and it looks as though they can be recovered also.

Figure 7 is an interesting picture of Betulia taken with the image orthicon system. Notice the stars and Betulia bracketed by the marks and note the shifting position in the very short time of fifteen minutes. The interesting point about them is that you get a sharp point, you see that the star background and asteroids are both points in the photographs. Ordinarily you either have to follow the stars and get the asteroid as a streak, or follow the asteroid and get the stars as a streak. If we are looking at a close approach object, it goes by so fast .. is very difficult to follow it. For one thing, you usually don't know it is going to be there until you accidentally discover one. All the very close approach objects have been picked up in this way, that is, accidentally. So you would not be able to sweep with it, and if you are following stars, the planetoid appears as a streak, and then of course the light intensity at any point is much lower. So you can actually follow it this way, you get a much higher intensity on a point and you get a much better chance of seeing it.

Now I want to go very quickly over some tables of interesting planetoids that we might want to study further in the future.

Figure 8 is a list of the twenty-five largest. Now we couldn't get all we wanted in here, but it goes down to sizes of about 100 kilometers, and all of them might be interesting in some respects. But if we want to actually travel there, we would like to have them with low orbital inclination. It makes an enormous difference as any of you astronauts know, if your inclination is five or even ten degrees out of the plane of the ecliptic.

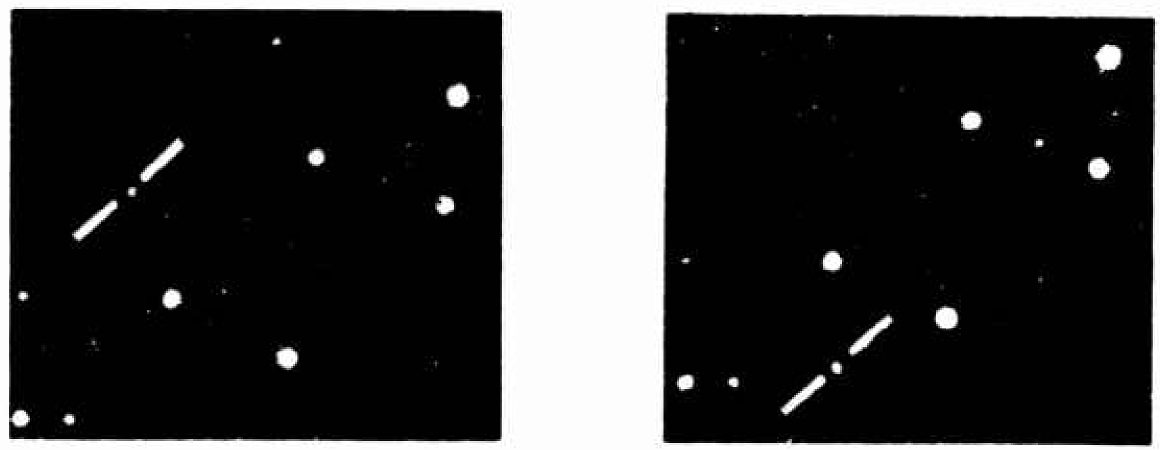
We have one, Massalia which is a very interesting combination of large size - a little better than 100 kilometers - and very low inclination - less than a degree.

Figure 9 shows some other large objects which all have low orbital inclinations - all of them less than three and a half degrees. And these objects all exceed 80 kilometers in diameter.

There is still another point of great interest if we are planning to go to the planetoids, or use them, and that is how close are they to the earth. So we want to look at the perihelion distance. On Figure 10, we tabulated some with small perihelia as well as low inclinations. In this group, we have very low inclinations, less than three degrees, and perihelion distances of less than two astronomical units.

One of these in particular is very interesting and that is Renzia. It comes in just to the orbit of Mars, 1.6 AU, and has a very low inclination, 1.9 degrees.

IMAGE ORTHICON PHOTOS OF BETULIA



RAPID MOTION OF THE CLOSE-APPROACH PLANETOID, 1580 BETULIA, IS SHOWN IN THESE TWO IMAGE ORTHICON PHOTOGRAPHS OBTAINED FIFTEEN MINUTES APART AT THE ORGAN MOUNTAIN STATION OF THE DEARBORN OBSERVATORY. WHEN NEAREST EARTH IN MAY, 1963, BETULIA WAS TRAVELING 5° PER DAY.

Figure 7

CAT. NO.	NAME	ABS. MAG.	INCLINATION OF ORBIT IN DEG.	COMMENTS
1	CERES	4.00	10.6	DIFFICULT TARGET
4	VESTA	4.20	7.1	
2	PALLAS	4.99	34.8	
15	EUNOMIA	6.08	11.8	
3	JUNO	6.36	13.0	
7	IRIS	6.76	5.5	ABOUT 120 MI. OR 195 KM
22	CALLIOPE	7.35	13.7	ABOUT 100 MI. OR 160 KM
20	MASSALIA	7.38	0.68	LARGE SIZE; SMALL INCLIN.
129	ANTIGONE	7.7	12.2	ABOUT 100 KM OR 62 MI.

Figure 8

NAME		INCLINATION OF ORBIT IN DEG.
THEMIS		0.815
EUTERPE		1.6
LUTETIA	[illegible]	3.1
FIDES	[illegible]	3.1
PALES	8.5	3.2
CYBELE	7.8	3.5

Figure 9

SOME ACCESSIBLE ASTEROIDS WITH LOW INCLINATIONS AND SMALL PERIHELIA

NO.	NAME	i	e	Rp	Ra
33	POLYHYMNIA	1.906	.333	1.92	3.82
135	HERTHA	2.3	.2075	1.93	2.93
149	MEDUSA	0.925	.065	2.04	2.32
182	ELSA	2.005	.187	1.87	2.96
228	AGATHE	2.56	.2405	1.67	2.73
240	VANADIS	2.11	.2055	2.12	3.22
244	SITA	2.82	.1376	1.88	2.48
291	ALICE	1.84	.0925	2.01	2.43
296	PHAËTUSA	1.74	.160	1.87	2.59
440	THEODORA	1.60	.1079	1.97	2.45
703	NOËMI	2.44	.1376	1.88	2.48
810	ATOSSA	2.59	.1800	1.78	2.58
822	LALAGE	0.695	.1548	1.91	2.61
1150	ACHAIA	2.37	.2028	1.75	2.63
1198	ATLANTIS	2.72	.3338	1.68	3.22
1204	RENZIA	1.89	.2948	1.60	2.92
1486	MARILYN	0.083	.1245	1.93	2.47
1536	1939 SE	1.52	.1955	1.77	2.63

Figure 10

Back in 1961 some of us were wondering what the ideal planetoid would be from the point of view of manned exploration and possibly using its resources.

We did not see any with exactly the right characteristics in the tables of asteroids, so we made one up, called Hypotheticus (Figure 11) which would travel along a transfer orbit from Earth out into the asteroid belt.

In other words, we wanted one with a perihelion of very close to 1 AU, a short period, a very low inclination to the plane of the ecliptic and a reasonably small size, so that we don't have a gravity problem in landing on it. Therefore, we said Hypotheticus would be three miles in diameter.

The date of discovery of this interesting object we said would be 1963, mostly for fun, but noting that we do discover these things pretty often, and there should be such an object. We saw no reason why there wouldn't be one with a diameter of three miles, perihelion distance about 1 AU, or maybe a million miles off. (Figure 12). We wouldn't care if it was within a million miles.

Now so far as I know, nobody discovered such a thing in 1963, in spite of our predictions, but what did happen was that in 1963 an object came up out of the dusty tomes in the library and was published in Middlehurst and Kuiper's book in the table on short period comets. And this is the object we have seen here before, Wilson-Harrington, 1949 G, and these are its characteristics on Figure 13. The perihelion distance is almost exactly 1 AU, the inclination 2.2 degrees - almost nothing. Several of the planets we hope to go to are even more than that. And one other point not on here, diameter 3.6 miles. So here was this object that had been lying around on a shelf in the libraries for many years. Why wasn't anybody interested in it? It was discovered back in 1949; it was listed as a comet, the astronomers were not thinking about going anywhere in the Solar System - most of them - and the astronauts were not thinking about going to comets. Most of the comets, of course, are not too attractive from the exploration point of view. In the first place, such a trip would be rather hazardous, but the worst thing is that trajectory energies are enormously high and it would be very difficult to land on most of the comets. The shortest period, one that most people talk about, is Encke's Comet which is over three years and even that would be pretty tough. You can send a probe there but if you actually wanted to rendezvous with it, that is another matter. The astronomers weren't interested in Wilson-Harrington and the astronauts did not know about it.

So let's see what they actually said about this thing in 1949, and the important thing, (Figure 14, this is a page from the Journal of the American Astronomical Society), the important point is here in the middle. "All the images are strong and entirely asteroidal in appearance, except for the small faint tail on the first two plates." They took plates over a period of a week and only on the first two plates was there any tail visible. There was no coma. In other words there was apparently a solid nucleus like an asteroid, and I think it is quite unfortunate that it was listed as a comet when it should more properly be considered an asteroid.

CHARACTERISTICS OF THE ASTEROID HYPOTHETICUS

Date of Discovery	–	1963
Diameter	–	3 miles
Mass	–	10^{15} lbs
Density	–	500 lbs/ft^3
Orbit Period	–	2 years
Perihelion Distance	–	1.01 A.U.
Aphelion Distance	–	2.18 A.U.
Semi Major Axis	–	1.59 A.U.
Inclination of orbit to Ecliptic	–	0^o
Eccentricity	–	.371
Perihelion Velocity	–	21 m.p.s.
Velocity Relative to Earth at Perihelion	–	3 m.p.s.
Impact Velocity	–	7.6 m.p.s.
Aphelion Velocity	–	9.68 m.p.s.
Required Change in Ap. Velocity	–	.0328 m.p.s.
Energy per pound Required for Orbit Change	–	465 ft lbs
Impact Energy per pound	–	24.9×10^7 ft lbs
Energy Ratio	–	53,400

Figure 11

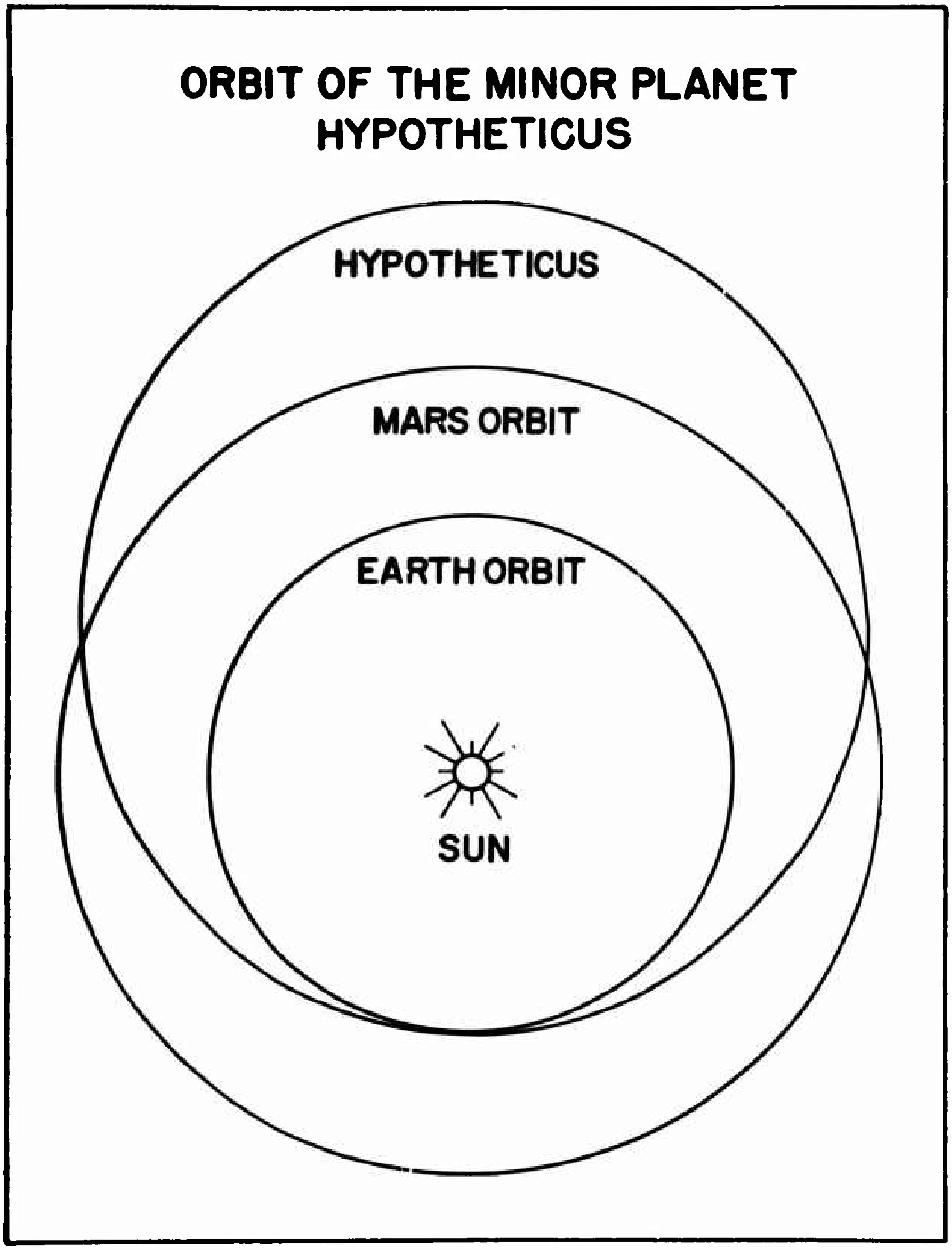

ORBIT OF THE MINOR PLANET
HYPOTHETICUS
HYPOTHETICUS
MARS ORBIT
EARTH ORBIT
SUN

Figure 12

TABLE OF THE ELEMENTS OF COMETARY ORBITS

NUMBER	–	1949 g
COMET	–	WILSON-HARRINGTON
T.(U.T.)	–	1949 OCT. 13·166
q	–	1.0276
e	–	0.4122
PERIOD (YEARS)	–	2.3 ?
i	–	2.20
COMPUTER	–	CUNNINGHAM

Figure 13

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1949 g was the first comet to be discovered with the new 48-inch Schmidt telescope on Palomar Mountain. It was found on two plates, taken in red and blue light in Pegasus on November 19·1 for the National Geographic Society-Palomar Sky Survey, by Albert G. Wilson and Robert G. Harrington. L. E. Cunningham, from prints of the photographs, estimated the magnitude as 12, and stated: "All the images are strong and entirely asteroidal in appearance except for a small faint tail visible on the first two plates; there is no trace of coma...." (H.A.C., 1052). His preliminary calculations of the elements of the orbit indicate that it was probably of short period, and the comet close to the Earth (0·16A.U.) at discovery. Unfortunately there was a month's delay in reducing the initial observations and, as no more have been reported since November 25, a reliable determination of the elements cannot be made, and the comet must be considered lost.

Figure 14

And even more unfortunate, note the last line, "the comet must be considered lost." Now that is true not only of this object but all the planetoids that have come within a million miles of the earth. They are discovered as they come by, they are going so rapidly that we get a very short view of the orbit and none of these very close objects have been recovered. That doesn't mean that they can't be recovered. Wilson-Harrington should have been visible for a period of about two months and was only actually observed for a week. So I think we can expect better luck in the future. There is even a possibility, although not too great a probability, of recovering this one. Some of Dr. Herrick's people think there is a chance, particularly if somebody has picked it up at some other time, and they can put the data together.

I think I will skip Figure 15 after just one comment. If you look at all the places you might want to go within the Solar System, and think about this in terms of getting rocket propellants to the strategic points, you can break down all your trips to less than 15,000 feet a second. This is the kind of thing that Dr. Steinhoff was talking about when he said that if we could make a recoverable vehicle and use it over again, continuously, in one stage, that this would be a very great benefit to space transportation costs. So 15,000 feet a second is a very nice velocity for a one stage hydrogen-oxygen rocket, and if you can break up your trip in this way, that is store fuel at these places and carry it there, perhaps from planetoids, you really have it made and you can travel all over the Solar System cheaply with chemical propulsion.

Now we talked about bringing propellants back from the planetoids to the orbit of the earth, and we have been thinking up until now at least about going out there with our vehicles and loading up the empty tanks with the propellants and bringing them back into Earth's orbit. Now maybe that is the way we will do it.

There is another possibility, a very intriguing possibility, and that is that we actually bring a whole asteroid back. And we do this by making a trip out there and making an expedition to the planetoid and at the perihelion point giving it a kick with some propulsion device which changes its orbit only a slight amount so that its perihelion coincides with the orbit of the earth. (Figure 16). Now we have indicated here we could set off a bomb something like the project Plowshare, or the Orion or a combination of the Plowshare and Project Orion. In other words, we explode several kilotons, that is, fairly small bombs to make this initial correction.

The most difficult thing in terms of propulsion comes when your planetoid passes near the earth, at which point you would have to throw it from heliocentric orbit to geocentric (Figure 17). That takes a lot more propulsion and it goes up to several megatons instead of kilotons. Whether you would actually use this kind of a propulsion system or not is not important here and it is much too early to go into detail. The important thing is that there is, at least theoretically, a method by which this could be done within the available capabilities of our present rockets.

In other words, the several megatons needed to do this could be carried by a single Saturn V Rocket out to one of these planetoids. We need another Saturn V to carry the

SPACE TRANSPORTATION VELOCITY REQUIREMENTS

Low earth orbit to escape	-	11,000 fps
Low earth orbit to high lunar orbit	-	12,000
Low earth orbit to Mars	-	13,000
High lunar orbit to surface of moon or to Mars orbit	-	8,000
Surface of moon to Mars orbit	-	15,000
Surface of Mars to low Mars orbit	-	15,000
Low Mars orbit to earth	-	10,000
Surface of Mercury to low orbit	-	11,000
Low Mercury orbit to orbit of Venus	-	12,000
Low earth orbit to orbit of Venus	-	12,000
Orbit of Venus to orbit of Mercury	-	9,000
Low Mars orbit to asteroids	-	15,000
Asteroids to Jupiter	-	10,000

Figure 15

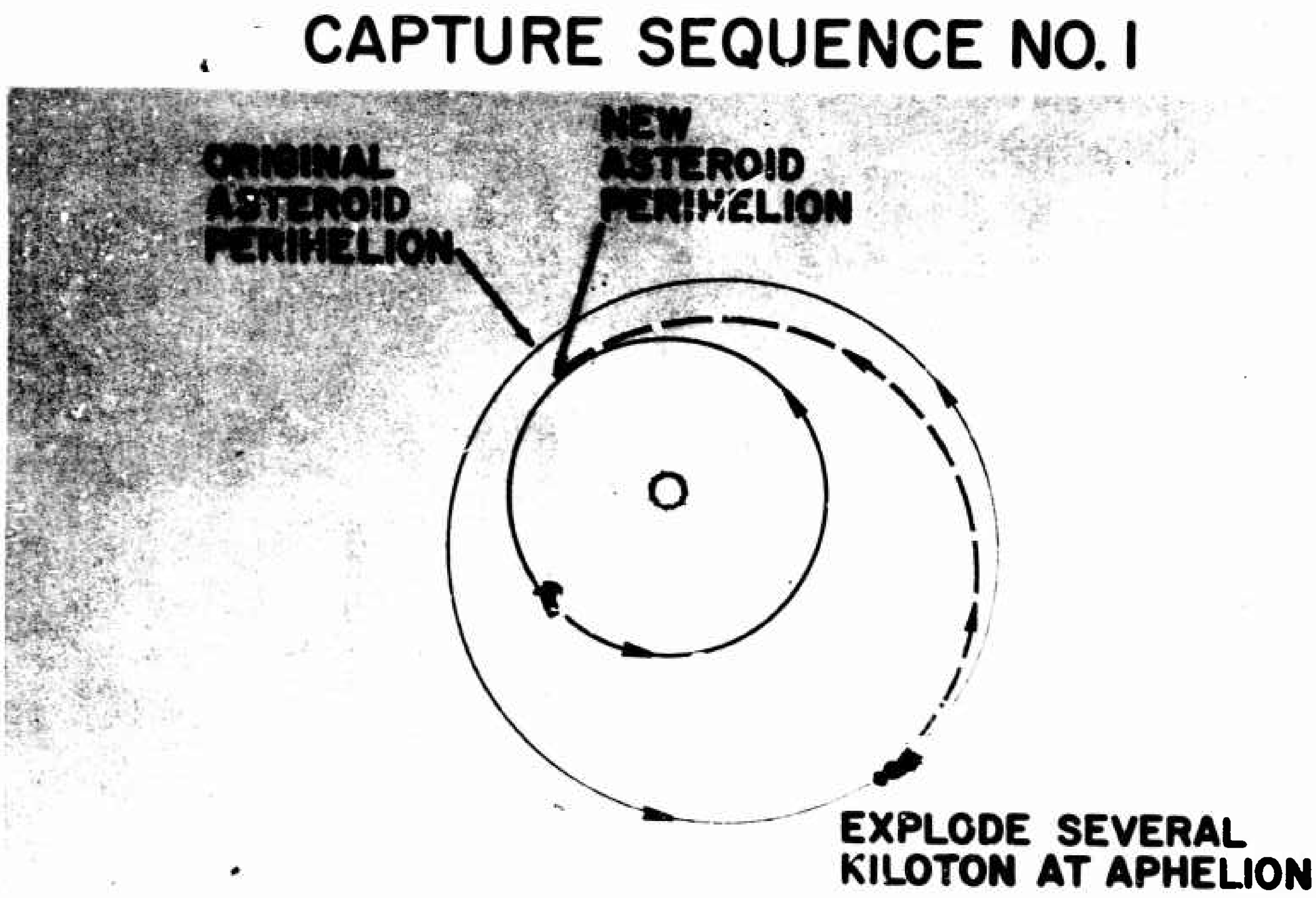

CAPTURE SEQUENCE NO. I
ORIGINAL ASTEROID PERIHELION
NEW ASTEROID PERIHELION
EXPLODE SEVERAL KILOTON AT APHELION

Figure 16

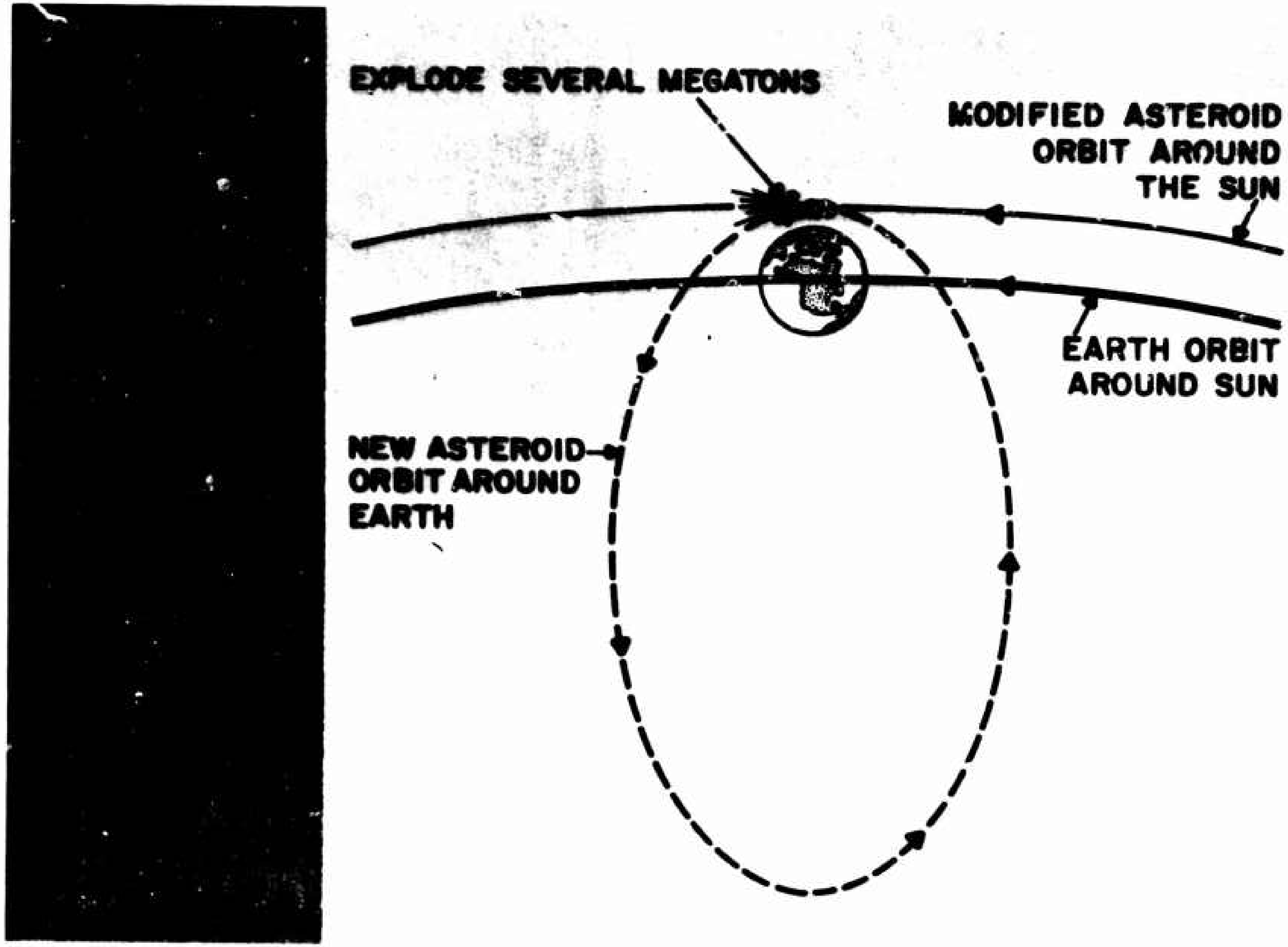

EXPLODE SEVERAL MEGATONS
MODIFIED ASTEROID ORBIT AROUND THE SUN
EARTH ORBIT AROUND SUN
NEW ASTEROID ORBIT AROUND EARTH

Figure 17

crew and some of the hardware, but with two Saturn V's you could conceivably work such an operation. Now whether you want to use this method or some other one is not the point at this time. The first thing is to go out there and reconnoiter and explore the thing.

If anybody is concerned about blowing up the entire planetoid when you set off the bombs, look at the crater size on Figure 18. This is the crater of a one megaton bomb in a rock planetoid about three miles in diameter. So you are not going to blow up the whole planetoid, if it is made of rock or iron.

If it is made of ice you would perhaps not want to use this method. On the other hand an ice planetoid would be so valuable that less efficient methods of propulsion could be employed.

Of course the capture of entire planetoids will not take place in the near future but we can begin to plan the first steps - the unmanned probes and the manned exploratory flights. We need not wait for nuclear rockets in the 1980 decade as we apparently must do for Mars. We can send men to a planetoid using only one or two Saturn V boosters as compared with eight to a dozen for a landing on Mars.

What new great manned exploratory flight shall we undertake after Apollo? Must we wait another ten or fifteen years for a Mars landing? A manned interplanetary flight to a minor planet could be made in the middle of the 1970 decade using our present booster technology. While Mars may seem a more exciting target in terms of immediate scientific payoff, the trip is far more difficult to accomplish. And the long term payoff from the planetoid flight may be at least as great when we consider the implications for reduced space transportation costs, planetoid capture, and extraterrestrial colonies.

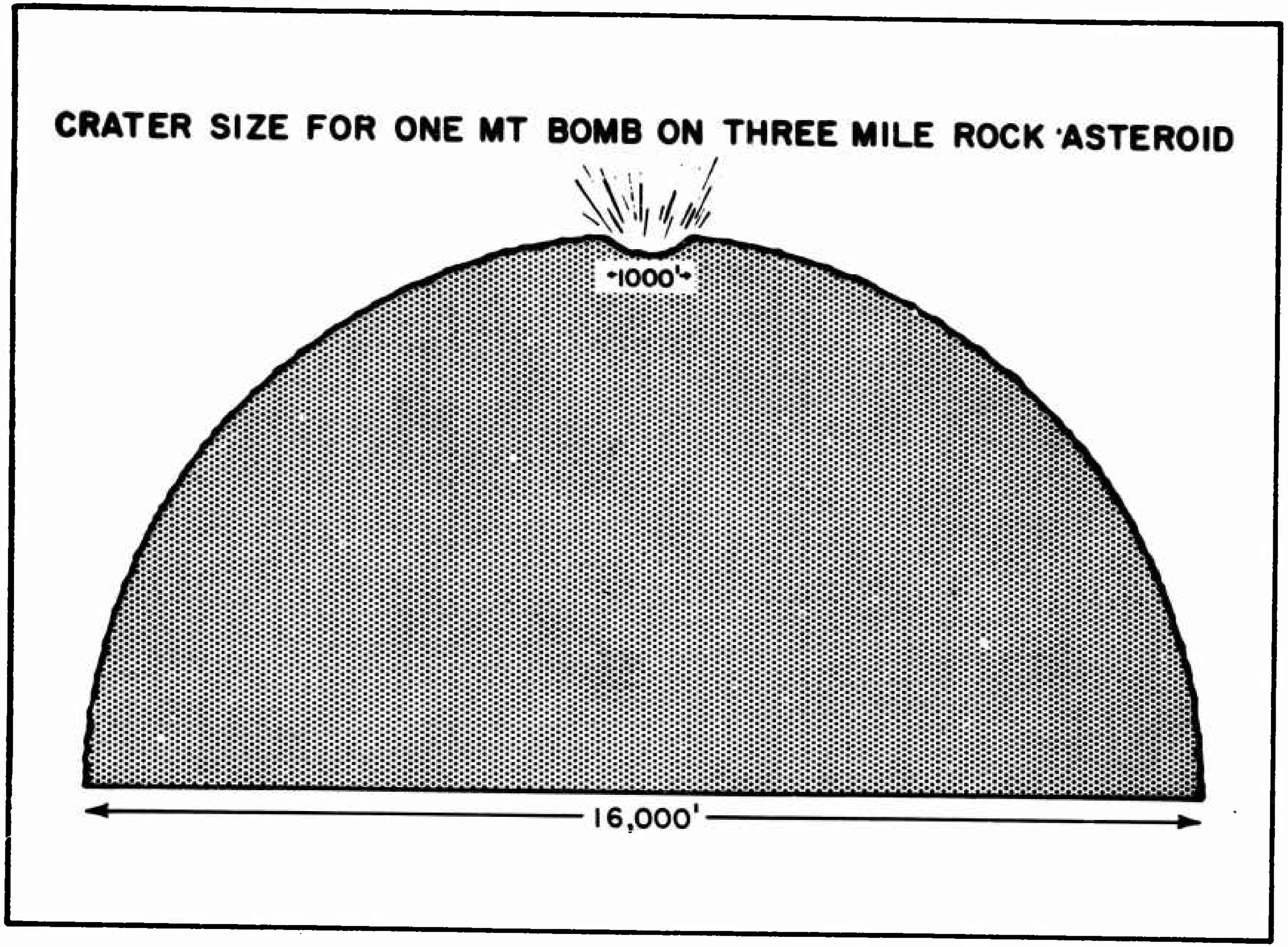

CRATER SIZE FOR ONE MT BOMB ON THREE MILE ROCK ASTEROID
1000'
16,000'

Figure 18

A METHODOLOGY FOR AN ECONOMIC ANALYSIS OF TRANSPORT AND MANUFACTURE STRATEGIES FOR THE RESUPPLY OF LUNAR BASE RESOURCES

David Paul, 3rd

OBJECTIVES:

The Logistics Requirements Subgroup of the Working Group on Extraterrestrial Resources undertook a study to determine the potential desirability and the eventual practicability of the use of extraterrestrial resources to enhance the accomplishment of future national space missions. Those missions involving the manned exploration and exploitation of the lunar surface, were designated as first priority and the group's principle effort was so directed.

The Subgroup's analysis will attempt to define initial, but necessary, criteria for the effective development of extraterrestrial resources. The Subgroup will highlight those resources whose successful development would suggest significant advancements toward completion of national space goals and thus be worthy of the initiation or continuation of applied research and technology studies. To establish this judgement the Subgroup chose a "manufacture or transport" analysis as a possible criterion of choice. The Logistics Analysis Committee was chartered with the determination, as a function of time and projected mission requirements, of lunar transportation system capabilities, availabilities, and costs.

The committee was also requested to conduct an operations analysis comparing the costs of supplying expendable items totally from earth with the costs associated with lunar surface manufacture. It was then necessary to relate this economic analysis to a resource demand analysis, thereby generating the data which the Subgroup requires to make appropriate recommendations.

SCOPE:

The philosophy to date has been to establish the methodology of an acceptable and logical approach to the problem, to make appropriate sensitivity analyses of the parameters affecting the economic comparisons, and to establish preliminary results depicting the area most fruitful for continued effort. When adequate resource priorities have been established and the various feasible processing techniques defined a more sophisticated approach to the economic trade-off should be attempted. In the interim the preliminary data generated by the Subgroup should prove indispensible for advanced planning purposes.

The transport option has been defined as a resupply technique wherein the complete replenishment of expended lunar station resources is accomplished via logistic rockets.

Once the extensiveness of the nation's space flight program has been postulated the availability of launch vehicle production and cost data allows this option to be readily analyzed and the operating costs assessed to an acceptable degree.

The manufacture option is defined as the supply of a lunar station expendable through the development and operation of an extraterrestrial processing plant. The analysis of the costs attributable to this option requires an understanding of the evolution and operation of postulated manned lunar exploration and experimentation stations, of the available equipments, and of man's capabilities in the lunar environment. Most probably these analyses will be subject to critical individual interpretation. It is assured that these early analyses can only develop a preliminary assessment of the manufacture option costs; how-analyses adoption of a consistant cost consideration should prove adequate for sensitivity analyses and initial economic assessments.

A manufacture vs. transport decision should not be considered without a "market assessment" upon which to project the economic analyses. A preliminary resource demand study was performed during the report period and should serve to orient the results of the economic "break-even" analysis.

METHODOLOGY:

Assumptions:

The analysis described herein has assumed an uninterrupted national space flight program which includes increasingly extensive manned lunar operations utilizing semi-permanent lunar stations to perform desired exploratory and experimental tasks.

The projected space programs which had to be assumed in order to develop the analysis have been based on a NASA budget which is restrained to grow no faster than the nation's gross national product. Obviously, this assumption places an upper limit on the extrapolation of data presented in the report.

The analysis has assumed that "learning" associated with production operations will act to decrease the cost of launch vehicle flight attempts as the number of such attempts is increased. "Learning" associated with both the use of common equipments throughout the various space flight missions and the occurrence of high production rates in any one time period has been factored into the analysis.

Of course, many minor weight, cost, and operational assumptions have been incorporated into the initial analysis described in this report. It is suggested that eventual sensitivity analyses will indicate that the relative nature of these assessments will not serve to drastically perturb the interpretation of the results.

Approach:

The charter mission of the Logistics Requirements Subgroup is interpreted by the author to be the determination of, and the eventual recommendation for development of,

those extraterrestrial resources which can feasibly be exploited, which are operationally desirable, are economically practical, and which are capable of development within the timeframe of interest.

As shown on CHART 1, the selection of promising resources obeying the constraints suggested above must consider the following factors: (i) the transport cost burden assumed if the resource is not exploited; (ii) the manufacturing cost burdens associated with set-up and operation of the postulated processing equipments; and (iii) a resource demand assessment to establish the desirability of the resource's development.

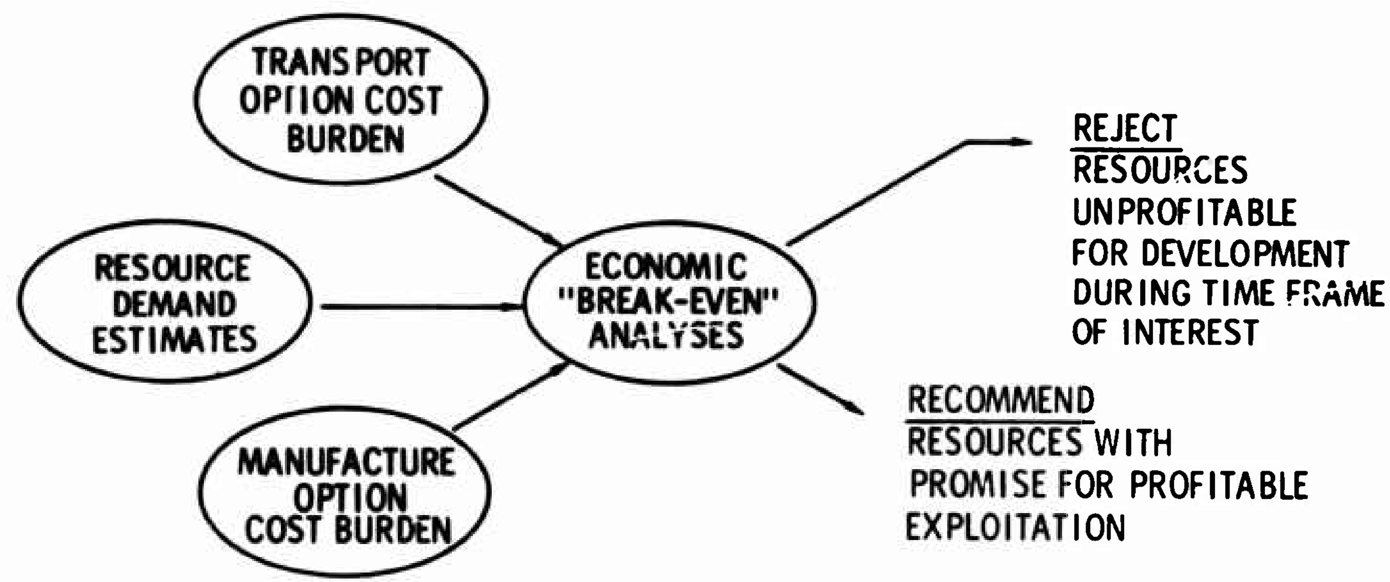
CHART 2 depicts graphically the methodology employed in the analysis of the Earth-to-lunar-surface transport option cost burden. The primary assumption, that of the extensiveness of the national space flight program, determines the launch vehicle availability and the flight history of the various flight systems. Once this postulation has been expressed, the calculation of the transport option cost burden is simple and straight forward. It was convenient to handle expendable consumption as a monthly rate which automatically set other parameters, such as launch rate, on the same monthly basis.

The manufacture option cost burden computational methodology is shown graphically on CHART 3. It is seen that this analysis is also dependent on the postulation of the extensiveness of the national space flight program to establish appropriate cost data for lunar surface man-hours and lunar cargo transport. In addition, a resource manufacturing or development concept must be delineated in sufficient detail to define the monthly requirements for: electrical power, equipment, re-supply items, man-power, etc.

A "market analysis" can be generated from the assumed national space program which assesses the lunar surface demand for a given resource as a function of time. These resource demand estimates will have a significant influence on the eventual recommendations made by the Subgroup. A graphic indication of the methodology applied to this estimation is shown on CHART 4.

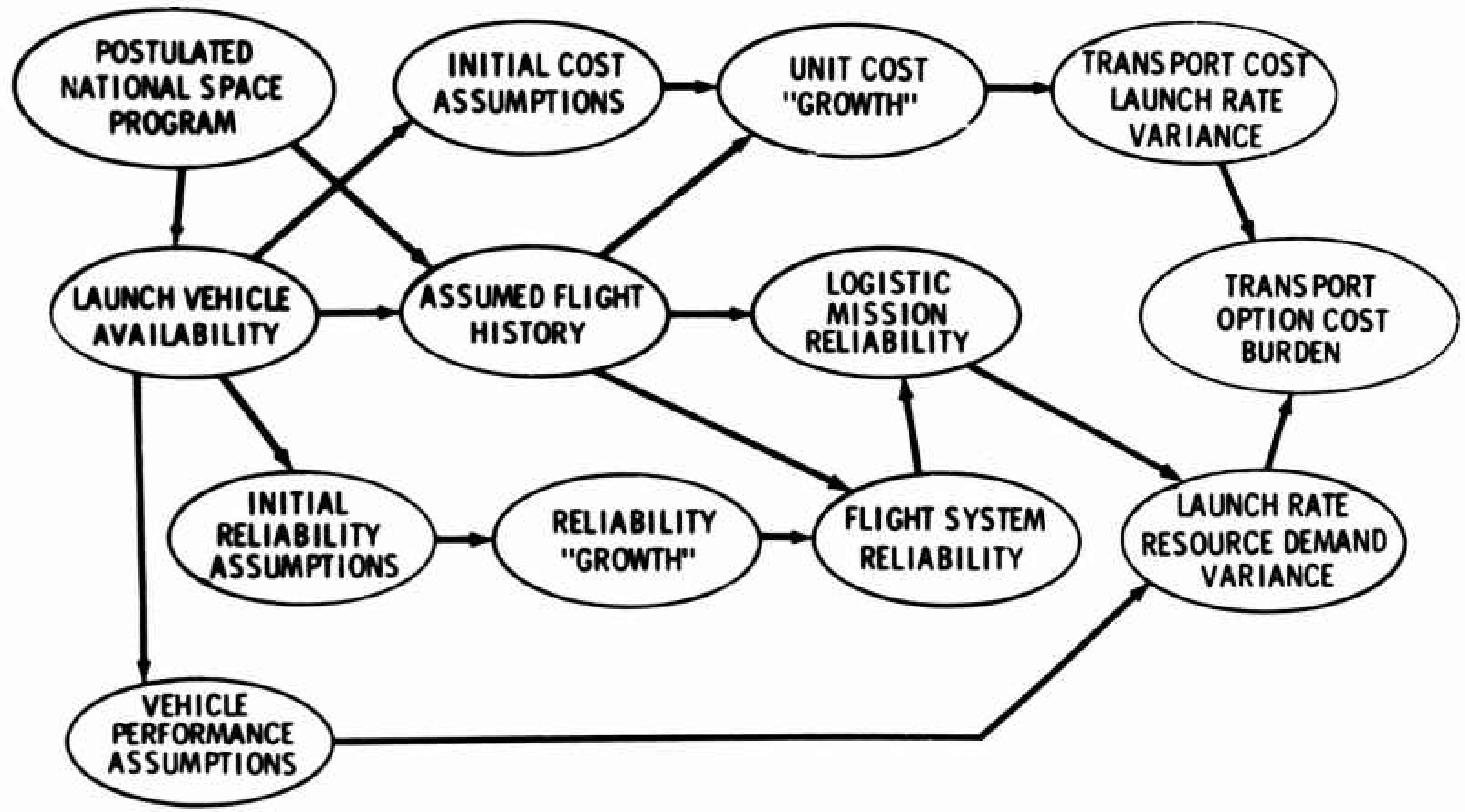
RESULTS:

The transport option cost burden parametrics, shown as the output of the analysis depicted on CHART 2, represented the primary goal of the Logistics Analysis Committee during the year. An Interim Report, dated July 1, 1964, was presented to the Subgroup during its working session of July 7 and 8, 1964 which discussed in detail the methodology associated with the transport option and presented appropriate cost burden results. An up-dated version of the summary chart shown in the Interim Report is reproduced here as FIGURE 1. It depicts, for the Saturn V logistic transport vehicle, the transport cost burden, as a function of the resource demand, for the various time frames of interest. The cost burden shown represents the costs associated with the more familiar term "direct operating cost." The resource demand, expressed as a monthly rate, is equal to the amount of resource transported to the lunar surface. The effects of unreliability during the various phases of transport are reflected in the cost burden values shown.



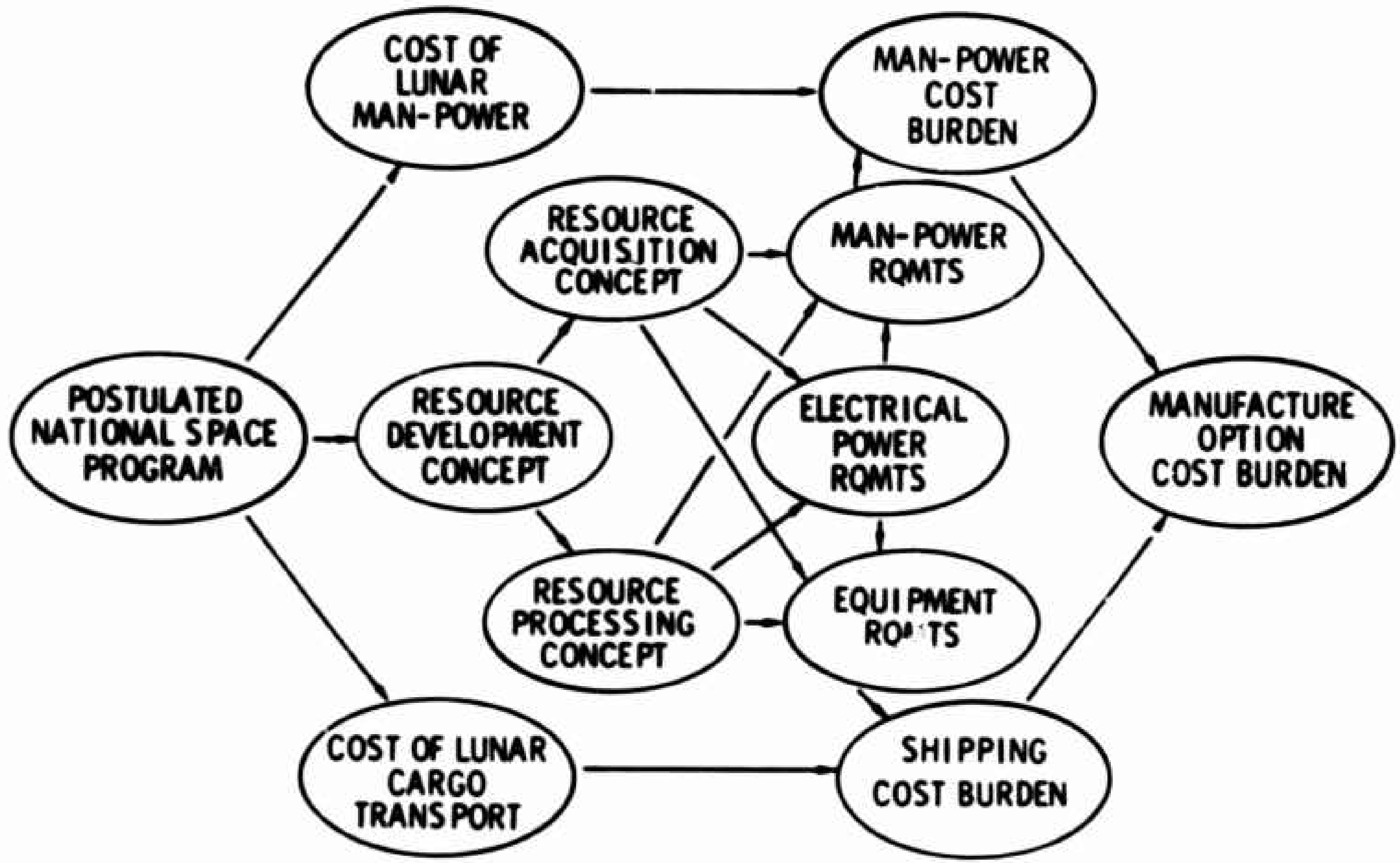
ECONOMIC ANALYSIS METHODOLOGY

CHART 1



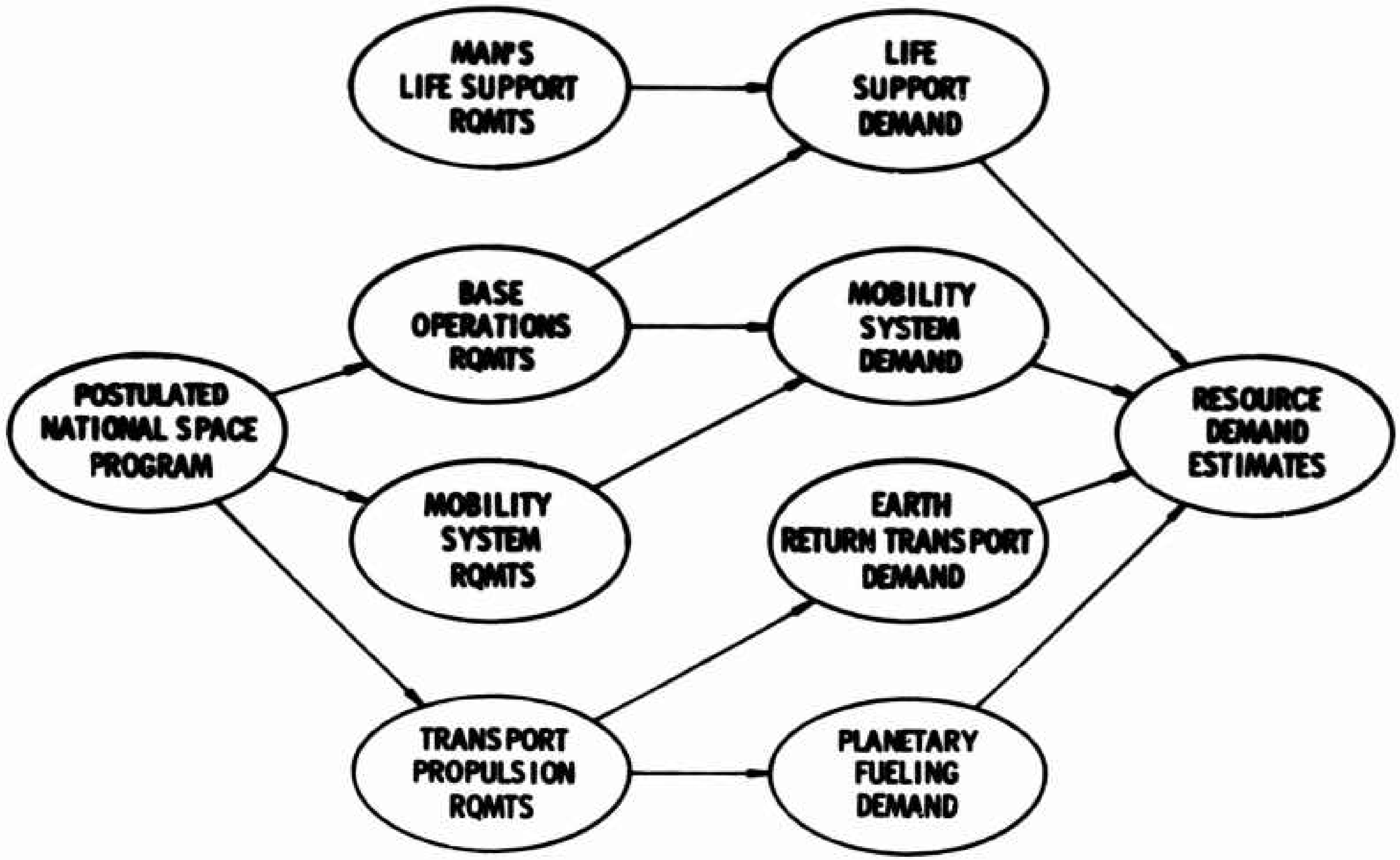
TRANSPORT OPTION COST ANALYSIS METHODOLOGY

CHART 2



MANUFACTURE COST ANALYSIS METHODOLOGY

CHART 3



RESOURCE DEMAND ESTIMATE METHODOLOGY

CHART 4

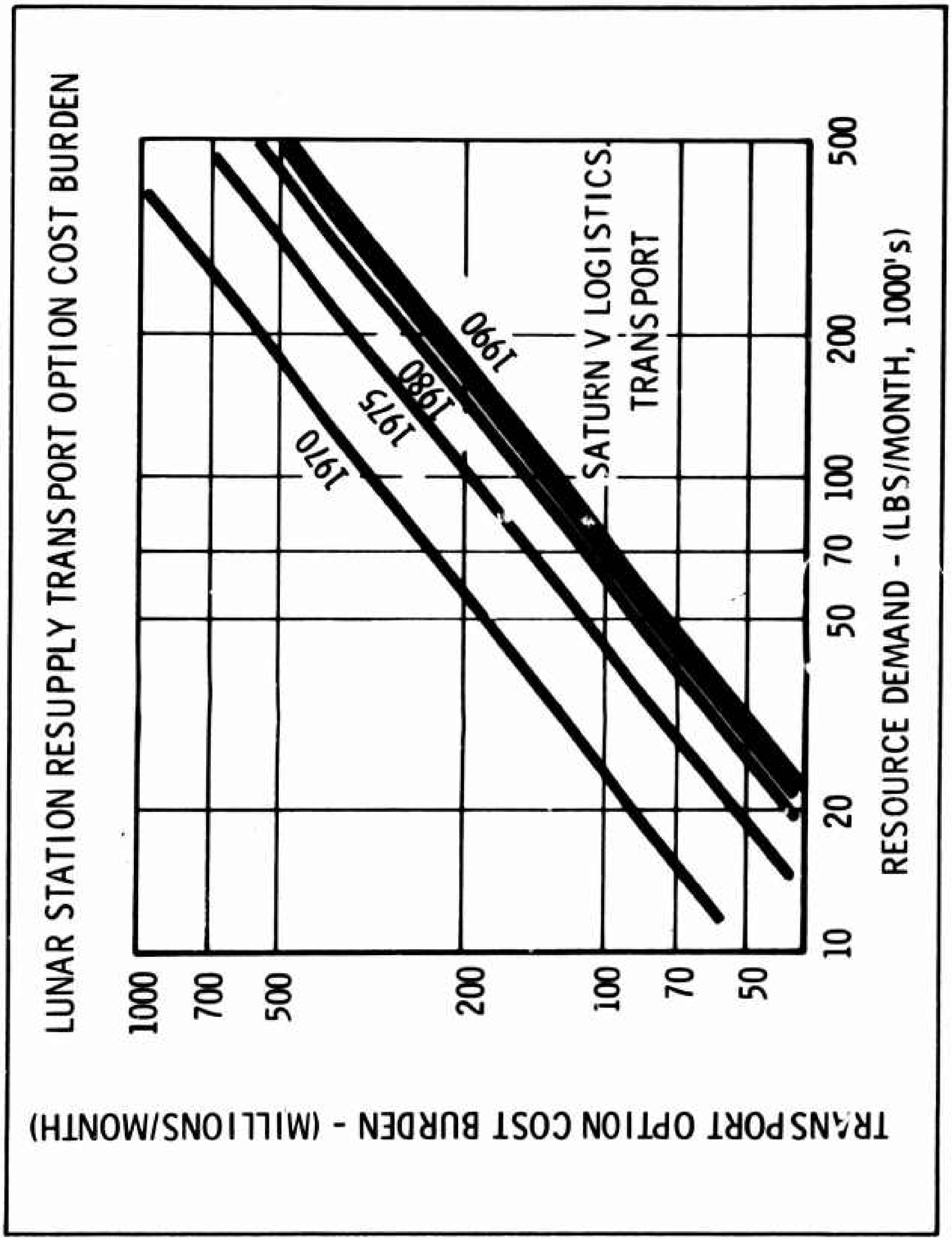

LUNAR STATION RESUPPLY TRANSPORT OPTION COST BURDEN
TRANSPORT OPTION COST BURDEN - (MILLIONS/MONTH)
1000
700
500
200
100
70
50
RESOURCE DEMAND - (LBS/MONTH, 1000's)
10
20
50
70
100
200
500
1970
1975
1980
1990
SATURN V LOGISTICS TRANSPORT

FIGURE 1

Since the postulated national space program has such an influential effect on the results of this study, the assumed launch calendar, extracted from the Interim Report, is reproduced for reference as FIGURE 2. On this graph the flight history of the various flight systems comprising the Saturn V vehicle is shown as a cumulative total. It should be emphasized that the postulated program shows an expenditure of approximately 500 Saturn V vehicles over a 20 year period; ie., an average yearly launch program of 25 attempts. It is suggested that this program, while seeming ambitious at this time, may well prove to be a reasonable national committment to space exploration. It should be recognized that less ambitious programs show an appropriate increase in the unit costs for cargo transport and extraterrestrial man-hours which would tend to prolong the point in time at which resource manufacture becomes desirable. The postulation of an austere space program would, almost by definition, rule out any consideration of the exploitation of extraterrestrial resources.

Due to the fact that sufficient data describing manufacturing processes for extraterrestrial resources was not easily generated by the various Burden Committees within the Subgroup, the Logistics Analysis Committee was unable to complete its secondary charter task, that of conducting the economic analysis to determine appropriate "break-even" points in the transport vs manufacture decision, during this reporting period. It was decided therefore to concentrate on the development of the methodology associated with the analysis such that, as data becomes available, the various resources and their processing concepts can be analyzed on an equivalent basis.

Some data, describing a postulated lunar surface oxygen processing plant, has been received from Dr. S. D. Rosenberg of Aerojet-General Corporation who has recently been investigating the associated chemical processes under a NASA contract sponsored by the Office of Advanced Research and Technology. This data was extremely helpful in establishing various criteria for the comparitive methodology. While some preliminary results have been generated concerning the economic analysis for this concept, they have not been sufficiently developed for presentation at this time. It is certain that these results can be incorporated into the next progress report.

In an effort to describe the methodology and the expected results of future economic analysis, a family of curves representing the manufacture option cost burden for a typical resource processing concept has been sketched and is shown as FIGURE 3.

It should be emphasized at this point that the curves shown on Figures 3, 4, and 5 only represent typical results expected from the development of the analysis; the scales shown on these Figures are not necessarily representative of any real process or space system.

FIGURE 4 shows the manufacturing cost burden curves with the resource demand estimates superimposed as uncertainty bands which, varying with time, represent various levels of effort within the scope of the national space program.

Since the transport option cost burden data (see FIGURE 1) is plotted to the same coordinates it is possible to overlay these curves and thereby determine, for any given

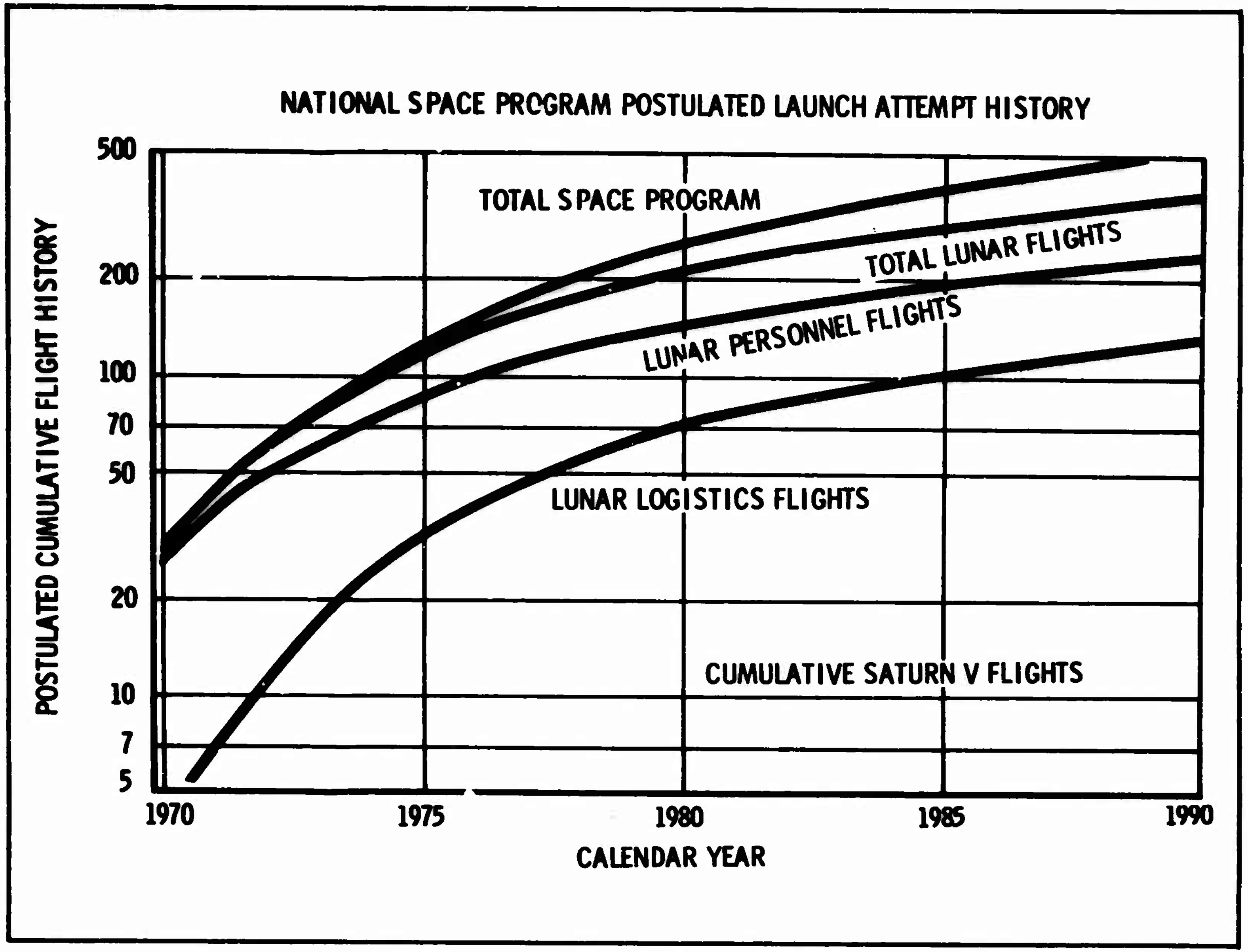

NATIONAL SPACE PROGRAM POSTULATED LAUNCH ATTEMPT HISTORY
POSTULATED CUMULATIVE FLIGHT HISTORY
500
200
100
70
50
20
10
7
5
1970
1975
1980
1985
1990
CALENDAR YEAR
TOTAL SPACE PROGRAM
TOTAL LUNAR FLIGHTS
LUNAR PERSONNEL FLIGHTS
LUNAR LOGISTICS FLIGHTS
CUMULATIVE SATURN V FLIGHTS

FIGURE 2

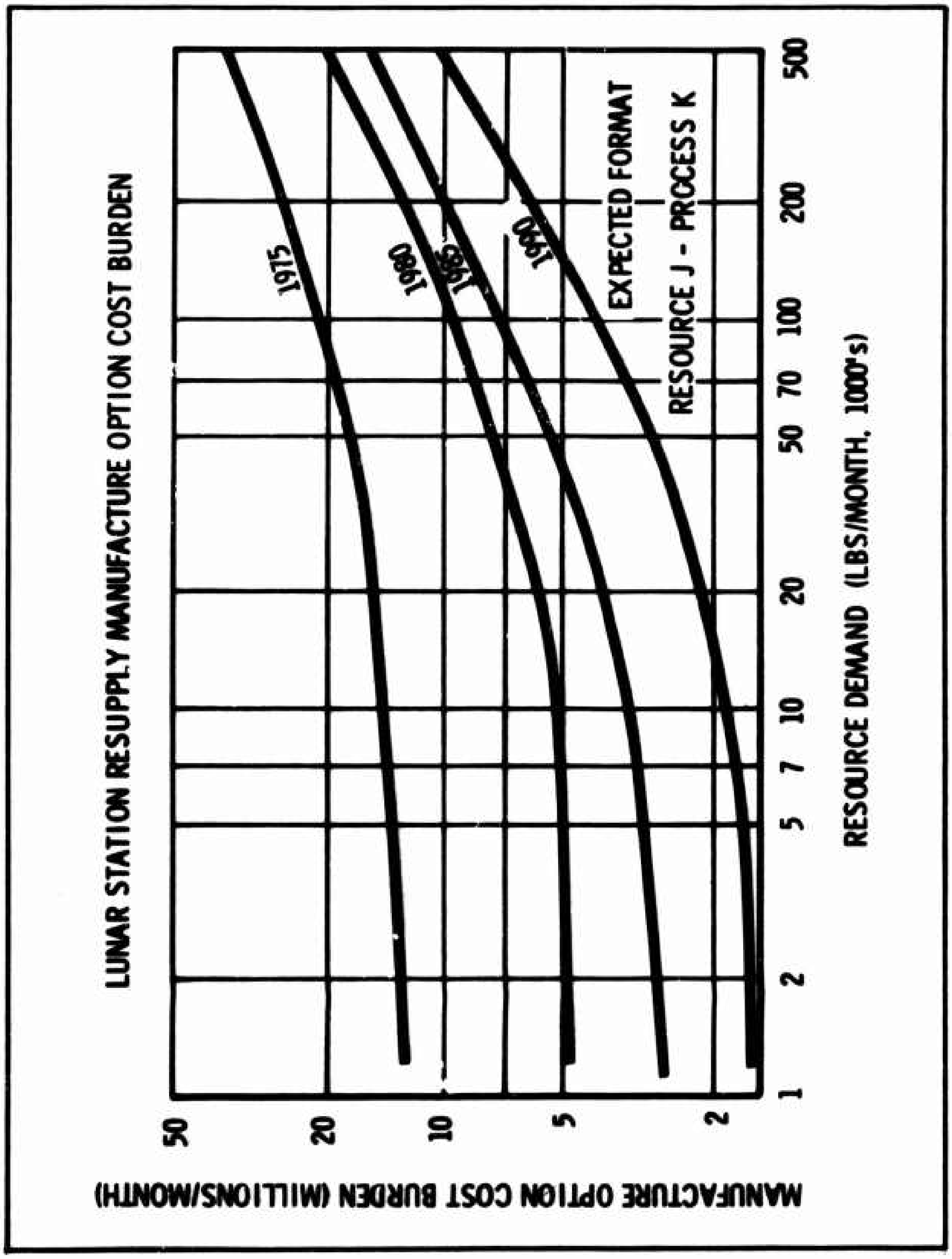

LUNAR STATION RESUPPLY MANUFACTURE OPTION COST BURDEN
MANUFACTURE OPTION COST BURDEN (MILLIONS/MONTH)
50
20
10
5
2
1
2
5
7
10
20
50
70
100
200
500
RESOURCE DEMAND (LBS/MONTH, 1000's)
1975
1980
1985
1990
EXPECTED FORMAT
RESOURCE J - PROCESS K

FIGURE 3

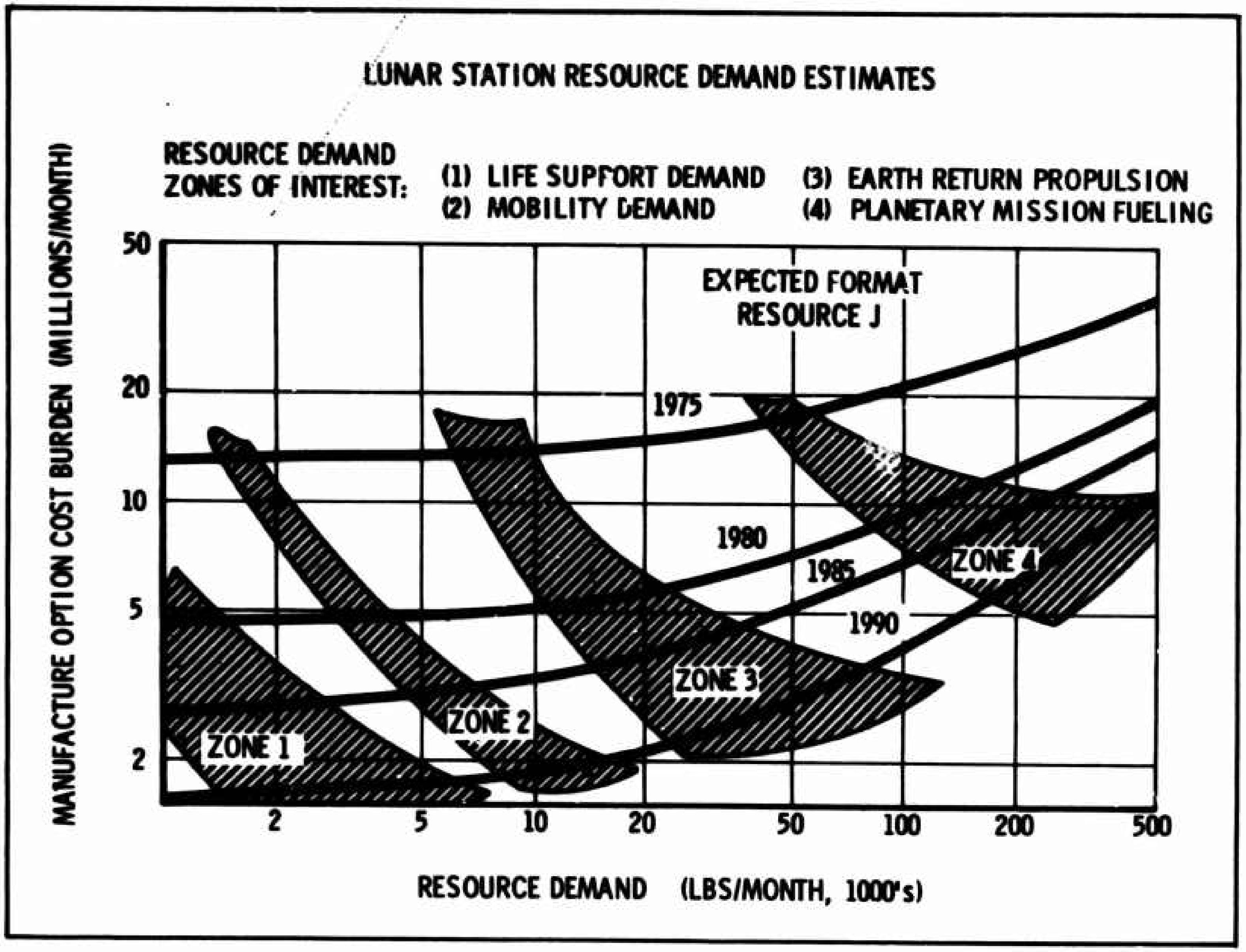
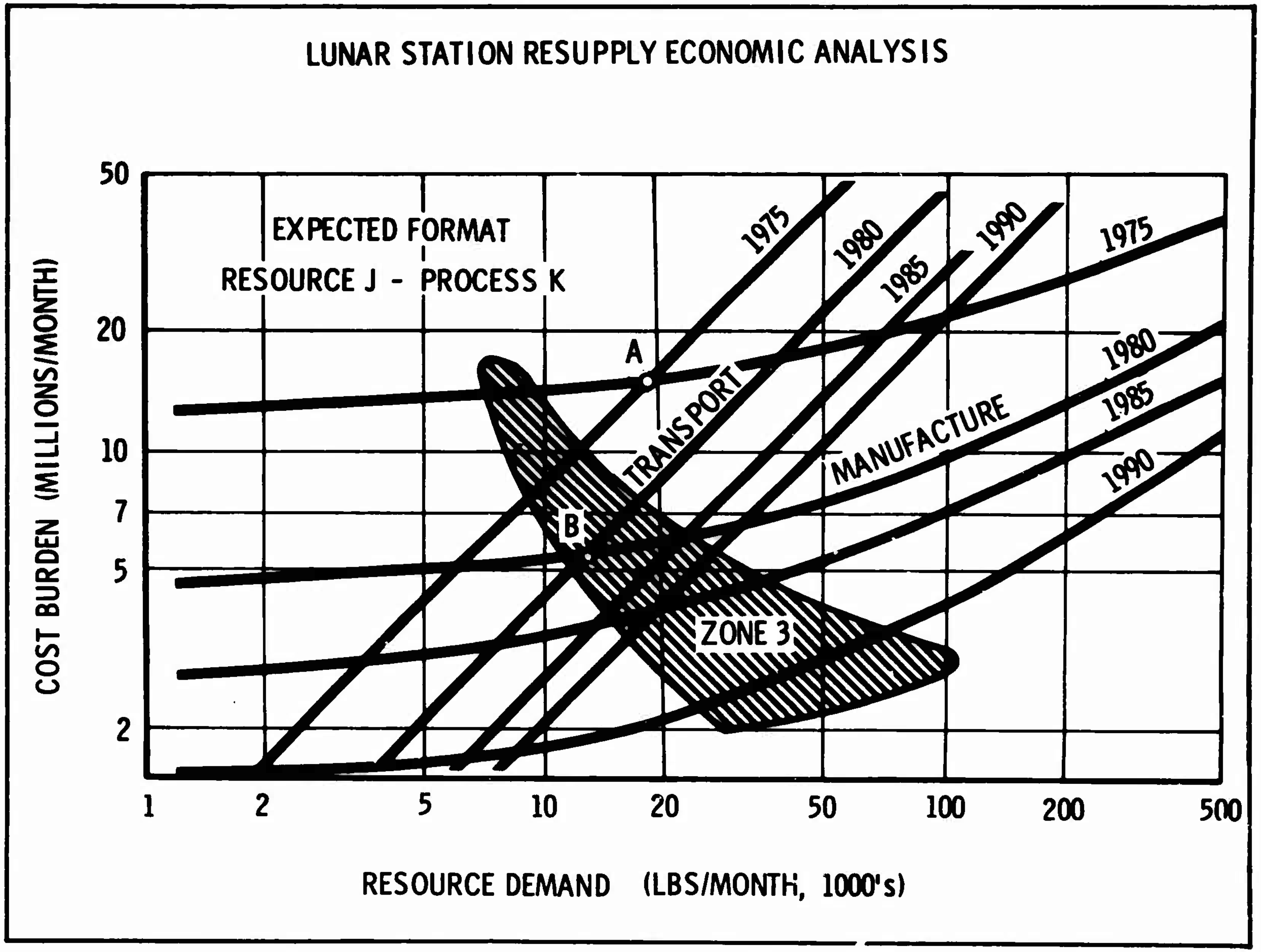

LUNAR STATION RESOURCE DEMAND ESTIMATES
RESOURCE DEMAND ZONES OF INTEREST:
(1) LIFE SUPPORT DEMAND
(2) MOBILITY DEMAND
(3) EARTH RETURN PROPULSION
(4) PLANETARY MISSION FUELING
EXPECTED FORMAT RESOURCE J
1975
1980
1985
1990
ZONE 1
ZONE 2
ZONE 3
ZONE 4
MANUFACTURE OPTION COST BURDEN (MILLIONS/MONTH)
50
20
10
5
2
2
5
10
20
50
100
200
500
RESOURCE DEMAND (LBS/MONTH, 1000's)

FIGURE 4



LUNAR STATION RESUPPLY ECONOMIC ANALYSIS
EXPECTED FORMAT
RESOURCE J - PROCESS K
COST BURDEN (MILLIONS/MONTH)
50
20
10
7
5
2
RESOURCE DEMAND (LBS/MONTH, 1000's)
1
2
5
10
20
50
100
200
500
TRANSPORT
MANUFACTURE
1975
1980
1985
1990
1975
1980
1985
1990
A
B
ZONE 3

FIGURE 5

time frame, the resource demand required to make the manufacture option economically desirable. If the break-even point is seen to also lie below a band representing the potential market (ie. the resource demand) then, of course, the particular manufacturing concept under analysis could be considered as a potential means to satisfy the lunar surface demand for that resource and should be recommended for further study. FIGURE 5 shows a sketch describing the circumstances discussed above and represents the expected results of the economic analysis.

A preliminary analysis has been generated for the optimistic, but easily analyzed, situation wherein lunar surface ice deposits are postulated to be readily available. Mining, melting, electrolysis, and liquefaction operations were considered in the transformation of the ice mineral into liquid oxygen. The transport option data was extracted from Figure 1, shown earlier. The economic analysis of this situation is shown on Figure 6. It can be seen that a "break-even" point between the transport and manufacture strategies exists in the 1970 time frame if the LOX demand exceeds 30,000 pounds per month. Since this use rate is greater than the requirements estimates, it is apparent that manufacture cannot be considered in this time frame as an economic enhancement to lunar operations. For the 1972 time frame, an economic assessment would indicate that the manufacture option should receive further consideration. By 1975, the analysis predicts that savings of $10 - 15 millions accrue each month by employing the manufacture option, if 10,000 pounds of liquid oxygen are required per month to operate the base. An analysis of the development costs associated with the processing equipment should be performed to substantiate the "break-even" point time frame. If the predicted savings will then adequately amortize the capital outlay associated with process development, the manufacture option could be recommended.

SUMMARY:

The high costs associated with extensive logistics transport from Earth to the lunar surface should encourage the search for methods which might reduce this burden. One concept, among others, would be to utilize extraterrestrial resources where possible to minimize the transport load. Economic, or break-even, analysis should be performed for each available resource and its associated manufacturing concepts to limit the development of the schemes to those which show the most promise as a space program adjunct.

An alternate approach to reduced space transport costs, in direct competition with extraterrestrial resource development, would suggest the development of less costly launch vehicles and thereby a reduction of the cargo transport burden. The development of a reusable Post-Saturn booster capable of transporting much heavier payloads, the achievement of high energy nuclear upper stages, the establishment of reusable, orbit-to-orbit systems employing advanced orbital rendezvous techniques and orbital launch operations, or various combinations of these concepts holds the promise of significant reduction in the cost per pound of lunar cargo. It is important that these possibilities be factored into the analysis.

It is believed that a technique has been developed which can be used to make a preliminary assessment of the worth of postulated extraterrestrial manufacturing plants within various possible postulations of the space program.

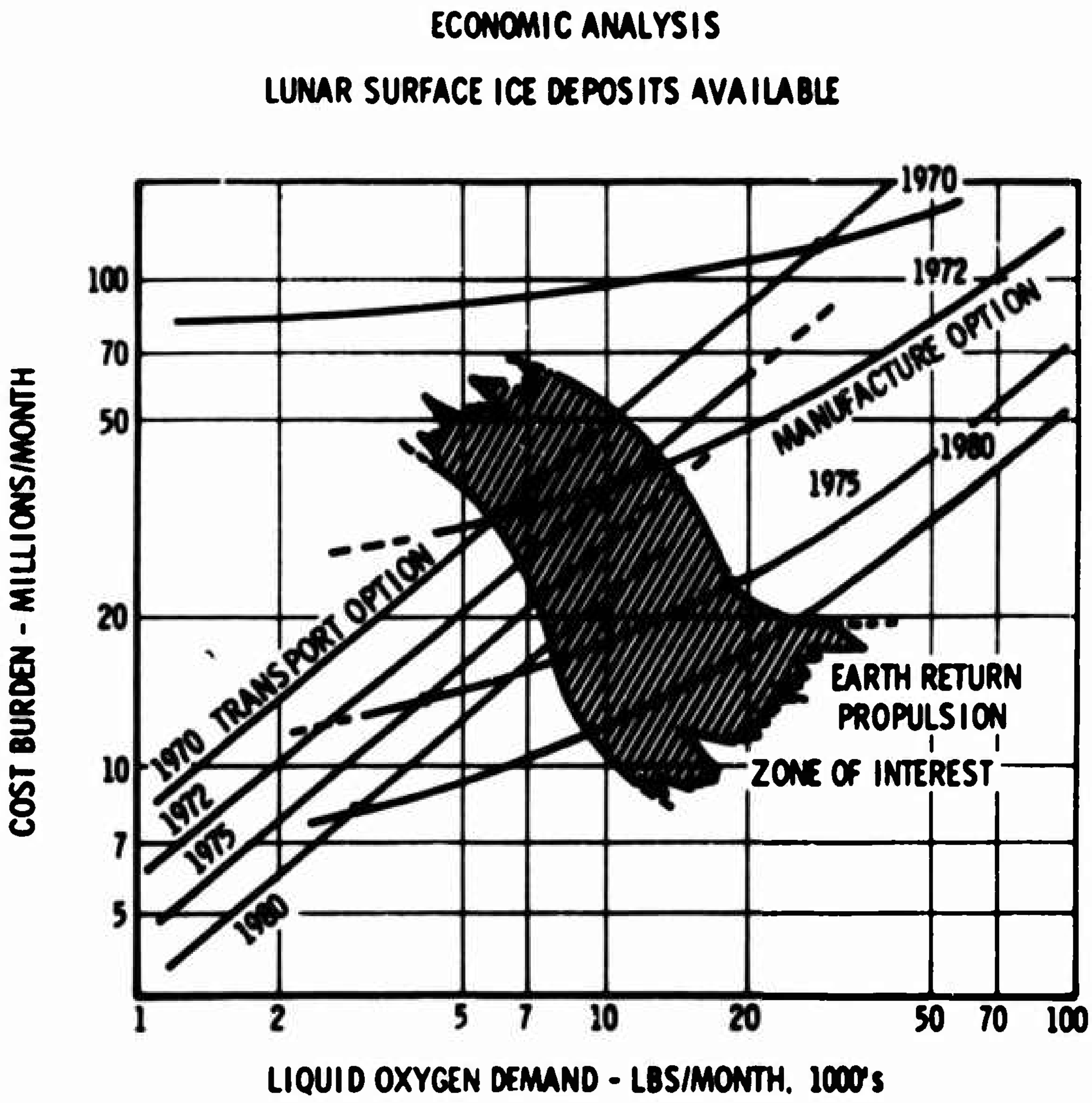

ECONOMIC ANALYSIS
LUNAR SURFACE ICE DEPOSITS AVAILABLE
COST BURDEN - MILLIONS/MONTH
LIQUID OXYGEN DEMAND - LBS/MONTH, 1000's
100
70
50
20
10
7
5
1
2
5
7
10
20
50
70
100
1970
1972
1975
1980
MANUFACTURE OPTION
1970 TRANSPORT OPTION
EARTH RETURN
PROPULSION
ZONE OF INTEREST

FIGURE 6

From initial operations with the technique it appears that the desired break-even points can be located and analyzed. It is suggested that the Subgroup's goal of selecting and recommending promising schemes for resource development can be achieved.

PROJECTION:

It is anticipated that data will become available during the next few months which will allow the analysis technique to be exercised for a spectrum of processing concepts. The Committee will thus be able to refine and generalize the methodology while learning to interpret the results of the initial efforts.

A computerized version of the technique would prove invaluable in sensitivity analyses which can lead to real understanding of the interactions of all the parameters and of their influence on the break-even point. The development of a machine routine will be considered during the coming months.

The consideration of launch vehicles other than Saturn V will be continued and the transport cost burdens established.

DISCUSSION

DR. STEINHOFF: I would like to make a few remarks concerning Mr. David Paul's paper, and call his attention to a report by RAND, which was published in connection with the Post Nova studies (RM-3501). It contains a detailed economic analysis of the Post Nova mission portion, and also includes an analysis of the cost of propellants. If you were to make a comparison of your considerations with those of RAND, you should actually have an opportunity to consider the expenses of having the propellants produced here, as compared to the cost of logistics bringing these here. It would show us the benefit of utilization of local fuel production.

I thought that this would be something you would like to know. It certainly shows that we need to have more people look into it. There are probably many bits and pieces published here and there which would be quite valuable to our Working Group if brought together into real context.

DR. EDSON: There are other situations, terrestrial ones, to which this same form of analysis is applicable, for instance, the development of underdeveloped countries which switched over from a dependent colonial existance to an independent or semi-independent industrial mode of operation. More particularly, the analogy can be shown in such operations as Anartica and Greenland and other places on Earth. Have you run across, in your studies, any literature, or back-up information, that might help to mature the analysis or throw light on our problem?

MR. PAUL: No, Sir, I have not. I have not investigated the literature on this point. It might, however, be a very interesting search.

DR. EDSON: I should think that if analyses of this nature have not yet been performed then one of the earlier areas for practical application of the analysis could be Anartica or Greenland to effectively test the answers. I can help to make the appropriate contact in this matter if someone else can't do it faster and quicker.

LUNAR BASE MISSION CREW
NUTRITION SUBSYSTEMS OPTIMIZATION

C. W. Craven
D. L. Dyer
R. G. Lindberg

ABSTRACT

Space crew diet need not be varied, but should be formulated for proper fat-protein-carbohydrate balance. Missions under six to twelve months duration will carry all food. Longer missions will quickly start regenerative (photosynthetic) systems.

INTRODUCTION

In reviewing elements of space crew nutrition (food, water, and waste management), many studies and proposed schemes can be found in the literature (1-6). These are for crews varying in size from one to several members and for missions lasting up to several months. All of the studies approach the problem in a similar manner in that man's metabolic requirements are met by providing typical foods to which he has become accustomed through many generations of social and economic pressures. Various workers have considered this approach necessary since a well-fed man from both the metabolic and esthetic point of view is judged best as a performer. Human experience does not fully support such an approach to feeding and the dynamic importance of food. Through the ages, man has used many unique substances for nutrition. At one time or another, he has eaten just about anything that could conceivably have food value (7). There are numerous cases of survival and epic-making explorations during which man performed exceptionally well while limited to meager rations or subjected to actual starvation.

The present review has been made to outline man's energy requirements and suggest possible new ways of meeting these requirements for a lunar base. For these missions, men will probably be required to perform light housekeeping chores and make such scientific observations as might be required in operating a solar observatory. For missions lasting only a few months, foods can be supplied from the earth, if sufficient attention is given to the selection of high energy low bulk substances. However, for longer missions, provisions must be made to obtain foods from lunar resources since the cost of continued resupply from the earth will be prohibitive. It is expected that adequate supplies of water and minerals will be available at the lunar base through reclamation of waste products in the environmental control system and perhaps from surface rocks. An unusual amount of ultraviolet energy is to be expected since radiation from the sun will not be subjected to atmospheric filtering. Lunar food producing units, i.e., algae tanks, plant tissue culture vats, hydroponic gardens, and beds of edible fungi might be

supported from waste products and the available lunar resources.

Man's dynamic living processes are reasonably well understood. Food substances vital to these processes are converted or degraded through well defined metabolic pathways to furnish tissue-building elements and are oxidized to provide required chemical energy. The total process of metabolism is dependent upon adequate supplies of oxygen and water, the former as an oxidizing agent, and the latter to afford an optimum wet reaction medium and transport mechanism. Food substances necessary to adequate nutrition include proteins, fats and carbohydrates. In addition, vitamins, certain minerals, and water are required.

REQUIREMENTS

Proteins fulfill essential roles in the body, affording sources of nitrogen and amino acids contributing to tissue structure. Of the amino acids that have been recognized as physiologically important, eight are not sufficiently synthesized in the body's metabolic pool, and must be supplied in foods (8). This group of essential amino acids includes isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan and valine.

Fats in the diet are an important source of energy. On a weight basis, fats are twice as rich in calories as either carbohydrate or protein. In addition to furnishing the essential unsaturated fatty acids, linoleic and arachidonic, fats serve as the carrier for fat-soluble Vitamins A, D, E, and K.

Carbohydrate in the diet is essentially an energy source. However, the body interconverts carbohydrate, protein and fat in the metabolic pool so one is the source of another within certain limits. The simple carbohydrates (sugars and starches) are readily digestible and efficiently utilized by the body, but the complex carbohydrates (cellulose, hemicellulose, and lignin) are not completely digestible and yield bulky intestinal residues that add greatly to the problems of waste disposal.

Vitamins recognized as essential include: Vitamin A (vision, cell differentiation, bone growth), thiamine (carbohydrate metabolism), riboflavin (tissue respiration), niacin (tissue respiration), ascorbic acid (cellular enzyme systems), Vitamin D (calcium metabolism), Vitamin B6 group (co-enzyme systems), Vitamin B_{12} (enzyme systems), folacin (nucleic acid synthesis), pathothenic acid (coenzyme A), biotin (enzyme systems), Vitamin E (tissue metabolism), Vitamin K (blood processes).

Important inorganic dietary mineral elements include: calcium (skeleton and teeth), iron (hemoglobin and enzyme systems), sodium and potassium (osmotic equilibrium), phosphorus (skeleton and teeth), magnesium (bone and catalysis for cellular reactions), copper (enzyme systems and blood formation), iodine (thyroid hormone), fluorine (bone and teeth). Essential trace elements include cobalt, zinc, manganese, molybdenum, and bromine.

Man is a sort of water-producing machine, producing about 7-10% more water than he takes in (9-12). In general, water is produced at the following

rate (13):

103 g H_2O/1000 kcal protein, or 0.41 g H_2O/g protein

150 g H_2O/1000 kcal carbohydrate, or 0.60 g H_2O/g carbohydrate

119 g H_2O/1000 kcal fat, or 1.07 g H_2O/g fat

Thus, if provisions are made to reclaim water in a closed environment, man's water requirements can be met without outside supplies.

In considering energy requirements, it is convenient to choose a reference man (in this case, a man: age 30-40 years, weight, 155 lbs., height 5'9", surface area 1.85 square meters) since metabolic rate is closely related to age and size (14). A number of reviews and studies have been made to define daily food and oxygen requirements for man during a space mission. A recent analysis (15) outlines possible savings in oxygen subsystem weight and adopts the following material balance.

Minimal Requirements (lb/man-day)	
Oxygen	2.00
Water (beverage and in food)	5.00
Foods (dry basis)	1.25

This quantity of food provides 3000 kcal based on a theoretical "food molecule" molecular weight 1002, 53% carbohydrate, 26% fat, and 21% protein. The 3000 kcal requirement can possibly be lowered to 2400 kcal when consideration is given to effects of reduced gravity (16). Such a lowered caloric requirement would reduce the dry weight of food to 1.00 lb/man day.

DIET

After extensive feeding studies, Sargent et al (13) recommended that the 2000 kcal of a restricted "survival" diet be distributed in the proportions of 15% of the calories from protein, 52% from carbohydrate, and 33% from fat. This is equa . to a weight distribution of 18% protein, 64% carbohydrate, and 18% fat. With this diet, 2400 kcal would be provided in 1.08 lb of food. However, these recommendations were based on comparisons of the diet above with three extreme cases: a 100% carbohydrate diet; a fat-carbohydrate diet without protein; and a fat-protein diet without carbohydrate. While these comparisons were quite appropriate for study of survival diets intended to delay physical deterioration over a two-week period, the problem at hand requires study of less extreme variations. The possibility that reduced gravity will decrease caloric requirements is by no means established. It is quite possible that work in pressure suits, combined with the exercise needed to maintain good physical condition, will require increased energy.

In providing ordinary food, most workers have selected a wide variety of meals for preservation (normally dehydration) and packaging since they have considered these best from the standpoint of optimum weight and organoleptic acceptability. A recent proposal by Karstens, et al (6) lists 1.4 lb of dehydrated food per man-day; this in close agreement with work reported by Welch (17). The excess weight is largely due to the decreased digestibility

of such foods. The disadvantage of excess weight is readily apparent for long missions. In addition, lowered digestibility results in more intestinal wastes for disposal. Besides solid waste residues from digestion, there are several materials which tend to contaminate the air. A list of the principal contaminants has been prepared by Olewinski (18), and is summarized below.

From Feces and Flatus

Skatole
Indole
para-Cresol
Propionic acid
Ammonia
Carbon Dioxide
Hydrogen Sulfide
Methyl Mercaptan

These contaminants which result from incomplete digestion of foods (especially protein) must be removed since they are toxic, thus increasing the problem of waste disposal. The tedious application of complicated technological processes for waste disposal might be greatly simplified through the use of carefully selected low residue diets. Packaging and storage weights for a dehydrated diet might be reduced from an estimated 20% to less than 5% if carefully prepared diets were utilized.

Although human nutritional studies and feeding experiments have been quite limited during recent years, these studies have helped to define man's nutritional needs in terms of caloric intake as related to performance (13, 19). Dietary requirements and recommended allowances have been reviewed by the Food and Nutrition Board, National Academy of Sciences (20).

Synthetic chemical liquid diets suitable for normal growth and life span of rats have been described in detail (21, 22). Since these diets were formulated for rat feeding experiments, consideration was not given to their use for human feeding. However, the work did indicate that such diets were sound from the nutritional point of view and might be adapted to man should the need arise. More recently, an attempt has been made to adapt such a diet to human use to gain the advantage of low fecal output and precise control of diet composition (23). This development has been chiefly concerned with detailed assay techniques for determining purity of dietary ingredients, biological adequacy of the final formulation, long term stability and nutritional efficiency. Some feeding experiments have recently been completed in which human subjects were fed only a synthetic liquid diet for a six-month period (24). Volunteer subjects were able to complete the experiment without apparent psychologic or physiologic damage and at all times were able to do light work and exercise associated with the day-to-day process of living.

Composition of the synthetic diet is listed below:

Amino Acids - 70 g

L - Lysine	L - Alanine
L - Histidine	L - Glycine
L - Arginine	L - Aspartate
L - Tryptophane	L - Proline
L - Phenylalanine	L - Glutamate
L - Leucine	L - Glutamine
L - Isoleucine	L - Tyrosine
L - Threonine	L - Serine
L - Methionine	L - Cysteine
L - Valine	

Minerals

Ammonium Molybdate	Magnesium oxide
Cobaltous Acetate	Manganese acetate
Cupric Acetate	Potassium Hydroxide
Ferrous Gluconate	Potassium Iodide
Fructose - 1:6-Diphosphate	Sodium Chloride
	Zinc Acetate

Carbohydrates - 584 g

Glucose	Glucono - gamma-lactone

Fat - 2 g

Ethyl Linoleate

Vitamins

Vitamin A	Alpha - Tocopherol
Calciferol	
Benzoic Acid	Inositol
Ascorbic Acid	Niacinamide
Biotin	Pyridoxine
Panthothenic Acid	Riboflavin
Choline	Thiamine
Folic Acid	Vitamin B_{12}

These substances were dissolved in sufficient water to make 1 liter of formula diet. The mixture was fed ad libitum with daily consumption averaging 2000 cc, which amounted to 2.8 lb solids per day, and over 5200 kcal. In addition to the unusual amino acid content, the diet was apparently deficient in fat, being composed of 89% carbohydrate, 10.7% amino acid, and 0.3% fat. Subjects complained of frequent gastro-intestinal upsets including nausea. Variations in diet flavor, i.e., cola or fruit, afforded some relief.

In other feeding tests, obese subjects have been subjected to starvation for long periods of time without injury (25). Food was withheld to accelerate weight loss, and water was permitted ad libitum with selected vitamins. Although these subjects were all compulsive eaters, they were readily able to adapt to the regime, and usually experienced no hunger sensation after 2-4 days. One of eleven subjects continued for 117 days, losing 116 lbs. The mean loss, weighted by the length of each experiment, was 1.12 lb (506 grams)

per day. There were serious side effects in five cases. Because energy is derived largely from fat, ketosis may be a problem (13, 26).

These trials show that the human diet can be altered to an unusual degree and still be acceptable, indicating the feasibility of a completely formulated food for space missions. Such a food would be best for optimum crew nutrition, most easily stabilized for storage, and economical in weight and volume. The development of such a food is of great importance to the early lunar base mission. There is need for further study of diet composition. It is quite likely that a wide range of compositions will be acceptable when the quantity available is large. As the weight and caloric content of the diet are restricted, the range of acceptable compositions will be restricted.

FOOD PRODUCTION

Even if the food requirement can be cut to a very low level - say, one pound per day - it must eventually become an excessive burden on the transportation system. Such a burden could be removed only by food production on the lunar base. This brings up the question of whether food can be produced in the lunar environment; and if so, whether production would be practical. There are basically three schools of thought on means of food production, each of which is necessarily tied in with carbon dioxide-oxygen exchange.

1. Total chemical synthesis
2. Bacterial carbon dioxide fixation (chemosynthesis)
3. Photosynthesis

Total chemical synthesis has been recommended for conversion of carbon dioxide via carbon monoxide and formaldehyde to a carbohydrate mixture (27, 28). The only reported test was unsuccessful (28). The specificity required for food production appears to be very difficult to achieve in a strictly chemical system.

Bacterial carbon dioxide fixation employs various species of Hydrogenomonas which metabolize hydrogen, oxygen, and carbon dioxide to produce cell material and water (29). The food quality of the bacteria produced is not yet known.

Photosynthesis is, of course, a more familiar process, and could make direct use of one of the more obvious extraterrestrial resources, sunlight. Because of its obvious applicability, use of photosynthesis for space operations has been studied extensively; and here, too, there are problems. The familiar food plants have a very low net efficiency because of relatively slow growth, space requirements, and the high proportion of indigestible material such as cellulose, which they produce. Dr. S. S. Wilks (USAF/SAM) has suggested the use of duckweed for gas exchange and food production, but nutritional data are lacking (30). The unicellular algae have been extensively studied because of their applicability for carbon dioxide-oxygen conversion, but data are still not adequate. Studies with rats fed Chlorella have indicated fair digestibility, reasonably good protein quality, and no definite adverse effects (31). The only algal feeding experiments with humans indicated that pond-grown algae are not a good food and are not well tolerated at

levels above 100 grams/day (32). It remains to be seen whether algae grown in pure culture will be better for humans. It is also quite possible that other species of algae would provide better food. Various suggestions that algae be fed to animals (ranging in size from brine shrimp to beef cattle) must be ruled out for the present because of the great loss of efficiency for each added step in the food chain.

Assuming that it is possible to produce food at the lunar base, would it be practical? This question may be restated: Are there missions for which food-producing machinery would weigh less than the food needed? In the strictly mathematical sense, it is apparent that, for sufficiently long missions, a system producing even a small part of the required food will be lighter than a stored-food system - but how long must this mission be? The answer involves a comparison of the total weight of the stored-food life support system with the total weight of the food-producing one. If the second system were of lower total weight, the answer would be obvious, and this system would be used for all missions. However, all food-producing systems now appear to be heavier. In this case, the mission length in question, or "days-to-crossover", is determined through dividing the difference in system weights by the weight of food replaced per day. It seems quite unlikely that a food-producing system will be employed for installations to be used less than six months. For longer durations the probability increases considerably. During establishment of the station, personnel will at first have to be fed from earth-supplied provisions, with conversion to the regenerative system as soon as practical. A supply of completely formulated food will be of great value for long storage at the lunar base in case of emergency.

Several major questions remain unanswered:

1. What will be the actual caloric requirements for the lunar base environment?
2. Can the survival diet recommended by Sargent and Johnson (13) be improved for extended use?
3. How critical are the proportions of protein, fat, and carbohydrate in the diet?
4. How greatly does individual variation affect the answers to the previous question?
5. Can Hydrogenomonas bacteria serve as food, and to what extent?
6. Can algal composition be shifted toward a more desirable food without undue sacrifice of growth rate?
7. What are the total weights of the various possible life-support systems, each with the best available design?

RECOMMENDATIONS

A completely formulated diet for space crews should be developed to provide a known and dependable food source. The crew members should use this diet during training in order to overcome prejudices built up over years of eating common foods. This period will provide baseline data for physiological studies; and individual variations which could cause trouble will be detected in good time. The formulated diet will provide nutritional support until permanent facilities are established, and could be used as an emergency reserve

thereafter. The economics of resupply are of such magnitude that early provision must be made for supplementing the crew's food supply from materials produced at the lunar base.

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DISCUSSION

DR. MARK, of G.E.: I would like to make a statement that refers to what Dr. Lindberg said, that man will, in essence, eat anything, and man can adapt to fantastically cold temperatures, high atmospheres, and semi-starvation. We have a whole history of extremes that man can eat, ranging from torredo worms in the tropics to grasshoppers. In addition, a fisherman can keep his hands in water cold enough to freeze us, and keep his hands in it for hours. The Sherpas of the Himalayas can literally sleep in the snow that would freeze us, and can survive, but he would not be happy. Now I know that sounds facetious, but it is not. If you take those of us who went through the C Rations of World War II, now that gave us nutrition, but left us unhappy. The point I want to make is that we must condition the men to not only tolerate, but to accept different diets.

We have just had a very outstanding example of this. We have just run a whole series of tests with food in simulated space capsules utilizing diets and dehydrated food. In our most recent study we had two meals that were liquid, that were very tasty and a third meal during the day was dehydrated food (a combination of natural foods). Before our subjects went into this, they accepted the simulated space food very well, but after the second day, one of our subjects simply would not eat it.

MR. DOLE: I would like to say that I agree with the last comment from the floor very wholeheartedly. The armed services certainly found this out during the war. As a matter of fact in the Navy they are very cognizant of the fact that food has an awful lot to do with morale, particularly as exemplified by submarine duty where the submariners constantly bragged about the wonderful diet they had on the submarines, chicken and real cream, and so on, and this was a big thing to them. It has a lot to do with morale.

THE ECOLOGICAL COMPLEX IN EXTRATERRESTRIAL BASES

S. H. Dole

Writers have frequently suggested that, when human beings establish bases on the Moon or on Mars, we should create miniature replicas of our own natural ecological complex within sealed chambers, and that the reliable and time-tested processes that supply us with food, fresh water and oxygen on Earth are those best suited to extraterrestrial bases. The purpose of this paper is to examine the concept of an Earth-style ecological complex created within an extraterrestrial base, and to compare it with other kinds of life-support systems that might be used, at least in the earliest versions of such bases.

Several desirable requirements for life-support systems in extraterrestrial bases may be specified: high reliability, minimum weight transported from Earth, ease of installation and maintenance, effective conversion of metabolic waste products, and maximum use of indigenous supplies and materials. I will not attempt to examine all the conceivable varieties of life-support systems in the light of these requirements but will merely compare the principal classes of such systems, and point out the major factors bearing on their use in extraterrestrial bases.

For purposes of orientation, let us suppose that we could reproduce man's natural ecology in a lunar base, say, and on the same scale per capita that it exists on the Earth's surface; the approximate quantities of materials that would be present are shown in the table below.

Table 1

ECOLOGICAL SUPPLIES ON EARTH: PER CAPITA BASIS

Water	475,000,000 tons
Air	1,700,000 tons
Oxygen	400,000 tons
Carbon dioxide	1,250 tons
Total dry land area	12.2 acres
Cultivated land area	2.2 acres
Living plants	30 tons

It is immediately apparent that it would be impossible to transport man's natural environment to some remote base on anything like the same scale that it exists on the Earth. Nor would it be necessary since we are so bounteously over-endowed with basic ecological supplies. For example, fresh water consumption in the United States is about 120 gallons per person per day, which works out to a lifetime usage of only about 13,000 tons per capita. Similarly lifetime oxygen consumption is only about 25 tons per capita. Thus, some

of the figures of Table 1 represent quantities so large as to be al[illegible]aningless, compared with what would actually be needed in an artificial environment.

On the Earth's surface human beings have had very little effect on the existing supplies of oxygen, carbon dioxide, and water. Man and all the other animals, in the ecological complex of the Earth's surface, are relatively insignificant parasites, late comers on the scene, whose presence may be virtually ignored against the panorama of atmosphere changes that have been produced by photosynthesis in green plants over the past several billion years that life has existed on our planet. It is sometimes erroneously stated that plants supply us with food and oxygen while we and the other animals in turn supply the plants with the carbon dioxide and other nutrients they need, thus maintaining the intricate balance of nature. The implied general interdependence does not actually exist, however, as may be demonstrated from the fact that, historically, plants existed on the Earth for millions of years before animals appeared. We need the plants but they don't need us.

The earth's natural environment should not be considered a "closed ecology" in the usual sense of the phrase as used in life-support-system terminology. In an absolutely closed ecology, all metabolic waste products would be reconverted into usable materials: fresh water, oxygen and food, with 100 per cent recovery. While there is a great deal of recycling in the natural environment (some of the cycles taking many years for completion) there are also additions to and losses from the system. Carbon dioxide and juvenile water, along with other compounds, are being introduced into the system from volcanic sources; some organic matter is being lost permanently from the system through burial in alluvial sediments; some water is being lost through dissociation in the upper atmosphere with the subsequent escape of hydrogen. Some oxygen is permanently lost through the oxidation of inorganic minerals in the Earth's crust, and carbon dioxide is constantly being used up in the formation of insoluble carbonates in the oceans. Only the vast scale of the reservoirs in the system permits such slow recycling with the preservation of apparent steady-state conditions. If the Earth had smaller reservoirs of water, oxygen, and carbon dioxide, much more rapid recycling would become necessary.

It is clearly out of the question to reproduce the Earth environment quantitatively in an extraterrestrial base. The figures of Table 1 may be thought of as representing an upper extreme, however.

The lower extreme must be somewhat arbitrary, but could be approximated by the quantities of materials present in some minimal volume of air per man plus a reserve of one day's supply based on average metabolic requirements. On this basis, assuming a volume of 700 cubic feet per man for long-time residency and an atmosphere consisting of 50-50 oxygen-nitrogen at 7.5 psia, the required quantities are shown in Table 2.

Table 2

MINIMAL ECOLOGICAL SUPPLIES: PER MAN BASIS

Water	5 lb
Nitrogen	14 lb
Oxygen	18 lb
Area (7-ft ceiling height)	100 sq ft

With such a small reservoir of oxygen and water, recovery of metabolic wastes would have to be rapid, perfectly efficient and complete, and losses nil; otherwise any serious interruption in the regeneration cycle would quickly become fatal.

The above figures do not provide any volume for food production, food storage, energy supplies, or air and water regeneration. Of these, all but food production can be made to occupy a relatively small volume by using concentrated foods and physicochemical oxygen and water recovery techniques. It is true that some researchers in the field of algal-oxygen recovery hope to produce edible products made from algae that could provide for a large part of human nutritional needs, and in equipment occupying very little space. However, this remains only a hope at present and workable algal systems capable of sustaining human beings for prolonged periods of time have yet to be developed.

If higher plants are used as the source of food products in extraterrestrial bases, fairly extensive growing areas must be provided. When using ordinary but very intensive farming techniques, enough food can be grown on 0.2 acre (8700 sq ft) to take care of the nutritional needs of one person (current Japanese performance, cited by Harrison Brown).[1] It has been estimated that by using hydroponics the necessary cultivated area could be reduced to 0.05 acre (2200 sq ft) per person.[2] However, this is still a pretty large area (larger than the plan area of most family residences) especially as it must be completely enclosed and made gas tight.

On the average, only 20 per cent of the total weight of food plants is consumed as food by man, although for specific plants the edible fraction may rise much higher, e.g., sugar beet, of which 78 per cent is available as food. Consequently, after having harvested a crop, one is faced with the problem of recovering the carbon, water and minerals tied up in the roots, stems, fibers and other inedible parts of the plant. And, of course, one must replace the carbon dioxide and water the plant consumed in photosynthesis. Thus the waste parts must be incinerated, which, incidentally, poses a nice problem of air pollution control in a closed ecology.

Also, in a lunar base, at least part of the illumination for photosynthesis must be provided artificially in order to preserve the normal light-dark cycles required by food plants. During the long lunar day, natural sunlight, appropriately filtered and regulated, could possibly be used for growing crops. The human gardeners would have to limit their exposure to high-energy protons

particularly during periods of solar-flare activity, but it is possible that at least some crops would be able to tolerate the particulate radiation environment without deleterious effects. During the lunar night, artificial illumination would have to be supplied. In a Martian base, natural sunlight could probably be used exclusively to illuminate crops grown in heated hothouses. It is apparent that the use of food crops does not provide an easy answer to the food-supply problem in a completely closed remote ecological complex, because of the rather large growing areas that must be provided, which implies the transporting of large quantities of structural materials.

A great deal is known about the hydroponic culture of food plants and about the nutritional requirements of human beings, but there are still some areas where the current knowledge is not adequate. For example, what are the best combinations of crops to supply man with oxygen and the maximum digestible nutrients per unit area, which meet the necessary proteins and other dietary requisites of man? To answer this, some full-scale, long-duration experiments are needed, with actual material balance for steady-state operation. Some other areas needing investigation are: how best to recover reusable products from the inedible parts of plants; how best to utilize human metabolic waste products; procedures to prevent losses of air and water from the system; optimal designs of growing, living and working quarters; procedures to prevent the introduction of plant diseases and parasites into the system; a complete comparison of hydroponics with other systems for a moon base and for a Mars base. Hydroponic gardening in extraterrestrial bases appears to involve a number of problem areas, the chief one being the large quantities of materials that must be imported in order to set up the initial installation.

Two other general classes of regenerative life-support systems are also being considered for use in extraterrestrial bases: physicochemical systems and algal systems. The physicochemical systems include the recovery of fresh water from waste water by processes such as vacuum distillation and charcoal filtration,and the recovery of oxygen from metabolic carbon dioxide by inorganic chemical reactions such as hydrogen reduction and water electrolysis, or direct decomposition. Many different designs of photosynthetic gas exchanges employing various strains of algae for converting carbon dioxide into oxygen and also producing food are currently under development. Some of the advantages and disadvantages of the basic types of regenerative life-support systems are itemized below.

<u>Physicochemical systems</u>

<u>Advantages</u>: Can be made to be highly reliable, compact, low in weight, easy to maintain, and efficient, when used for oxygen and water recovery. The technology is already quite well developed.
<u>Disadvantages</u>: Not practical for food production, thus cannot create a completely closed ecology. Food supplies must be imported and stored. However, with highly efficient systems, resupply weights (including food and replacement of losses) could probably be held to less than two pounds per man per day.

Algal systems

Advantages: It has been predicted that algal systems will eventually become very compact and low in weight. Could supply part of food requirements in addition to carrying out oxygen recovery. Can utilize metabolic waste products more completely than physicochemical systems.
Disadvantages: Quite inefficient conversion of light into useful products. Algae are currently undesirable as food, and need elaborate processing in order to be converted into even marginally acceptable food for human beings. Maintenance, harvesting, and processing for food are bound to consume more man-hours than the operation of physicochemical systems. System more prone to failure, more sensitive to environment. Technology is still not very far advanced, and equipment is still bulky and inefficient.

Hydroponics

Advantages: Requirements for environmental control may be less critical than for algae; equipment less complex. Food products more palatable than algae. Completely closed systems may be possible. May make use of indigenous supplies and materials.
Disadvantages: Requires large volumes or areas in the extraterrestrial base; very inefficient in converting electricity into useful products, which becomes important if artificial illumination must be supplied. Produces large quantities of inedible by-products that must be processed. Technology for utilization in extraterrestrial base needs further development in Earth-bound experiments.

At the present time, it appears that the first versions of extraterrestrial bases will depend on physicochemical recovery of oxygen and water, and on imported food supplies. Later versions might bring in algae or hydroponics on a small scale, backed up by physicochemical systems, for experimental purposes. Ultimately, if very large colonies are constructed, hydroponics could become the mainstay of the ecological complex in lunar or Martian bases.

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DISCUSSION

DR. WELLS, of NASA: I have seen hogs eat coal. I often wondered about this. Do they eat this because of the exercise it gives their jaws, or is there a food value in the coal, because coal came from a plant life?

DR. DOLE: I would hazard a guess on this, that they eat it for the same reason some children eat dirt, whatever reason that is.

COL. CRAVEN: Most of these people have had some severe nutritional deficiency causing these strange cravings. From a nutritional point of view, it is unlikely that coal would have nutritional value. It is probably good to chew on like some people chew wheat straws, when they play football.

DR. STEINHOFF: Many of the birds eat all kinds of things and this is really to stimulate digestion and to reduce the size of things which birds have swallowed.

COL. CRAVEN: A bird has a craw, and needs pebbles and gravel, but a pig has a digestive tract about like a man.

QUESTION: Bone chewing by cattle is done, this is a common thing in phosphorous deficient areas. It is an animal response to a lack of phosphorous in the vegetation.

DR. AUSTIN: I want to comment on the coal. A poorer grade of coal very commonly has a number of soluble salts that give it a taste and you might find that pigs eat it for this reason.

DR. ROSENBERG, Aerojet General: I think if we are clever enough we can convert carbon dioxide into metnyl alcohol for the same weight penalty that we can convert carbon dioxide to methane, or carbon, because the conversion of carbon dioxide into methyl alcohol is another variant of the Fisher reaction or Sabatier or Bosh. By clever enough, I mean we have to discover the proper catalyst and reaction conditions, and those of us who have worried about a closed cycle system don't laugh about feeding astronauts alcohol. It is perfectly acceptable under emergency conditions.

MR. DOLE: I was under the impression that the known conversions were not nearly as clean and efficient as say the Sabatier reaction.

DR. ROSENBERG: The yields are poor, and you get a whole group of other alcohols.

SPACE VEHICLE ATMOSPHERE CONTROL SYSTEMS

STATE-OF-THE-ART SUMMARY

Edward B. Thompson, Jr.

Introduction:

Future manned space flight in the coming decade will be accomplished by vehicles having mission durations within the range of several days to several weeks. These vehicles which include Gemini, MOL, and Apollo will require space system capabilities only slightly advanced over the Project Mercury vehicle system capabilities. The Mercury program proved man's ability to exist in an orbital space vehicle of short duration which underwent transient conditions of gravity loads and the re-entry environment. The most important consideration to note, though, is that the Mercury vehicles had durations measured in hours and not days or weeks, and mission duration is the dominant factor leading to the selection of a particular method for controlling the vehicle cabin atmosphere. This fact is best understood by considering what function the atmosphere control system serves.

Fundamentally, the purpose of the atmospheric control system is to provide the compartment or compartments of a space vehicle with the desired atmospheric pressure, temperature, humidity, and composition. When the compartment under consideration contains a manned crew, the physiological requirements of the crew must be satisfied by this system.

In manned compartments, the primary functions of the atmosphere control system are those concerned with the regulation of the oxygen, inert gas, carbon dioxide, water vapor, and trace contaminants within certain allowable limits. This regulation is accomplished by various means, depending on the type of system used. Oxygen may be supplied from a storage system. Carbon dioxide and water vapor may be removed and dumped overboard, or reprocessed to recover oxygen.

All of these functions must be met in the case of each manned space vehicle regardless of its intended mission, crew size or mission duration. For short duration vehicles this is not a complex problem since oxygen may be supplied from storage containers and contaminants adsorbed by chemical agents. But as mission duration and crew size increase the requirements become so stringent that qualitative factors, as well as quantitative ones, affect the design of the atmosphere control system. The stored gas system becomes prohibitive from a weight standpoint and methods of recovering oxygen from carbon dioxide must be considered. The use of a regenerating atmosphere control system having many moving parts emphasizes the fact that "reliability" deserves increasingly more consideration in research programs as system complexity grows. Since the power requirements of the regenerating system are higher than those for a stored gas - Mercury type system, there is an added factor in the choice of the vehicle auxiliary power system.

This paper serves to review the state-of-the-art of atmosphere control processes for providing a one-gas and two-gas space vehicle cabin atmosphere. Leakage rate, power requirements, and reliability are also discussed. Finally, conclusions and recommendations are presented on research problems requiring additional effort..

Defining the State-Of-The-Art:

When a particular process is said to be state-of-the-art, it means that the technical community has a high degree of confidence in the operation of this process. The higher the degree of confidence or certainty that the process will accomplish its purpose is usually based on the quantity and quality of information available on the process. For example, lithium hydroxide for air purification is generally recognized as an excellent material for absorbing carbon dioxide since lithium hydroxide has been used as a carbon dioxide absorbent in industrial processes for over forty (40) years. The quantity of data compiled on the process is enormous and this data certainly existed prior to the conception and relization of a manned space program. The contractor responsible for the NASA - Mercury program was aware of the information on lithium hydroxide and applied it to the general Mercury mission requirements; that is, the duration and crew size of the vehicle as well as the basic purpose of the program. The short mission duration and one (1) man crew size of the Mercury vehicle impressed the idea that the atmosphere control system could be composed of well proven reliable components and processes without special emphasis on research programs to improve the state-of-the-art. This was also compatible with the fact that the Mercury astronaut leads a sedentary existence during flight and his oxygen requirement is minimal. It could be logically deduced that the oxygen supply requirements of the astronaut would be fairly constant and that steady-state performance of the atmosphere control system was required. The sum total of these findings was that the atmosphere control system should be composed of state-of-the-art processes and components or those in which the design engineers had the highest degree of confidence. There was no need to implement high risk research programs. This general approach which led to the selection and design of the atmosphere control system for the Mercury vehicles can also be applied to the planning and conducting of research programs for meeting future space vehicle atmosphere control requirements.

Research Approach:

First, it must be possible to postulate with reasonable accuracy what types of space vehicles will be operational in a particular time period. It must then be determined if atmosphere control applicable to these vehicles require additional research and development. Secondly, knowing the types of vehicles to be operating in this time period conveys general information on mission duration, crew size, and intended purpose of the vehicle missions. It then follows that the atmosphere control system requirements or at least an envelope of system requirements can be postulated. The system requirements dictate the type of atmosphere control processes which appear to be the most feasible for the space vehicle in question. The research engineer can then proceed logically to plan and direct exploratory development programs to laying a solid base of technology for postulating system configurations. It can also be determined, to an

extent, the technology of auxiliary power systems and methods of predicting gas leakage rates and consider these as factors in planning the research programs.

The research engineer can then plan the work starting from the known technology, available data, and degree of confidence surrounding the entire scope of atmosphere control methods thought to be feasible at initiation of planning. For example, it may be known at the onset of the research program that there are several different methods for removing carbon dioxide from a closed cabin atmosphere. A technical library would then be compiled on each of the methods. Using this library of information the researcher would arrive at a degree of confidence on the capability of each method and then identify the unsolved problems surrounding each method. These problems when identified would be categorized as to whether they could be solved by an analytical study or by a laboratory experimental program or a combination of both. Of course, it might be possible at this point to decide that one particular method is impractical for space vehicle application. The researcher is performing the important function of eliminating the impractical carbon dioxide removal methods. This ultimately results in a higher concentration of dollars and effort on specific research problems.

In an optimum research program planned to advance a specific atmosphere control process into a proven state-of-the-art classification, the research investigator initially directs the work to cover the more practical processes for effecting space vehicle atmosphere control. The system planners are consulted to determine the range of space vehicle capabilities desired in the foreseeable future. The atmosphere control systems applicable to these vehicles are then defined in the detail required for the investigator to focus his efforts on specific problem areas. As an example, it may be determined that a chemical-mechanical atmosphere control system which includes carbon dioxide reduction will be required for vehicles having mission durations exceeding three (3) weeks. The technical approaches of a research program to investigate carbon dioxide reduction processes would be defined as well as establishing analytical programs to determine the problems and peculiarities of designing a chemical-mechanical atmosphere control system. An assessment of the required operating life and total reliability of the system would also be accomplished. The analytical program for selection of a particular system configuration would be based on the factor of system operating reliability in addition to weight and power requirement optimization. Reliability becomes increasingly important as the mission duration of the vehicle increases and oxygen recovery by carbon dioxide reduction becomes increasingly attractive from a weight savings standpoint. The advantage of decreased system weight due to oxygen recovery processes is offset considerably, however, by the decreased reliability of the regenerating system. The reliability decreases simply because the regenerating system providing for oxygen recovery uses far more moving or dynamic components than a stored gas open system. It becomes necessary to build in spare components such as fans and pumps or complete redundant systems so that the system reliability is comparable to stored gas system reliability. The investigator now has the responsibility of not only conducting research on the atmosphere control processes, but also analyzing the effect of component reliability on total system design and performance. The results of these efforts serve as recommendations to the system planners.

Requirements of One and Two Gas Systems:

The atmosphere of the manned space vehicle consists of either pure oxygen or oxygen plus a bulk diluent gas such as nitrogen at varying total cabin pressures. Helium and neon are also considered as possibilities as a diluent gas. Both the one gas and the two gas atmosphere contain micro quantities of contaminants such as carbon dioxide and water vapor which must be controlled within permissible limits. The following Table 1, illustrates the characteristics and requirements of a One and Two gas system.

TABLE 1

Parameter	One Gas Oxygen Only	Two Gas Oxygen plus Diluent
Total Pressure	5.0 ± 0.5 psia	7.0 ± 0.3 psia
Oxygen Partial Pressure	4.7 ± 0.6 psia	3.0 ± 0.2 psia
Diluent Partial Pressure	--------------	4.0 ± 0.3 psia
Carbon Dioxide Partial Pressure	0 - 2.6 mmHg	0 - 4.0 mmHg
Trace Contaminants	Below Human Tolerance	
Temperature	75 ± 5°F	75 ± 5°F
Reliative Humidity	50 ± 10%	50 ± 10%
Leakage Rate (Estimated)	0.5 to 2.0 lbs. per day dependent on total cabin pressure.	

The tolerances required in accurately maintaining the desired constituent quantities pose the common problem for either system. However, there are advantages and disadvantages unique to each system. The One gas - oxygen "only" system has the advantages of simplicity of sensor instrumentation and lower gas leakage rate from the vehicle because of lower total cabin pressure. But it has the disadvantage of imposing a greater fire and explosion hazard than a diluted atmosphere. The Two gas - oxygen plus diluent system is advantageous because it poses less of a fire hazard. It has the disadvantage, however, of requiring extra sensors, valves, and atmosphere monitoring equipment thereby making it a less reliable system. The one gas system is preferred from an engineering standpoint because it is the simpler of the two systems. It is probable though that two gas systems will be used in missions exceeding thirty (30) days because of physiological and fire hazard considerations.

Atmosphere Control Processes:

A survey of the literature on research programs currently in progress was the basis for preparing Table 2, a summary chart of atmosphere control processes,

which the research investigator could recommend to the system planners. It should be mentioned however, that the information presented in Table 2 is incomplete for several reasons in a number of areas. First, because of the expanding scope of industrial and governmental aerospace research and development, new atmospheric control concepts are being evolved continually; time has not permitted detailed up-to-date analyses of all of these concepts. Second, critical analysis reveals that basic design data is not available even for rather well-known types of atmospheric control components, particularly those involving chemical reactions for removal or conversion of atmospheric contaminants. Finally, as is the case with any space vehicle system, basic process behavior in the absence of gravity is not yet defined for several types of atmospheric control processes involving phase separation.

TABLE 2

Process	Technique	Degree of Confidence
Carbon Dioxide Separation and Collection	Lithium Oxide	State-of-the-Art
	Lithium Hydroxide	State-of-the-Art
	Molecular Sieves	Exploratory Development
	Selective Membranes	Exploratory Development
	Condensation/ Freezeout	State-of-the-Art
Water Vapor Separation and Collection	Silica Gel	State-of-the-Art
	Molecular Sieves	Exploratory Development
	Wicking Materials	State-of-the-Art
	Condensation/ Freezeout	State-of-the-Art
Oxygen/Diluent Gas Storage	High Pressure Gas	State-of-the-Art
	Subcritical	Exploratory Development
	Supercritical	State-of-the-Art
Oxygen Generation	Superoxides	Exploratory Development
	Carbon Dioxide Direct Decomposition	Basic Research

	Water Electrolysis: Rotating Cell	Exploratory Development
	Reverse Fuel Cell	Exploratory Development
	Phosporous Penoxide	Basic Research
	Electrodialysis	Exploratory Development
	High Temperature Oxides and Carbonates for CO_2 Absorption and O_2 Generation	Basic Research
Trace Contaminant Removal	Activated Charcoal	State-of-the-Art
	Catalytic Burner	Exploratory Development
	Other Adsorptive Agents: (Silver Foam) (Magnesium Foam)	State-of-the-Art
Carbon Dioxide Reduction	Sabatier or Methanization Reaction	Exploratory Development
	Carbon Monoxide Reaction (Re-cycle)	Exploratory Development
	Bosch or Carboniza-tion Reaction	Exploratory Development
	Electrolytic Decom-position	Basic Research

Atmosphere Control Systems:

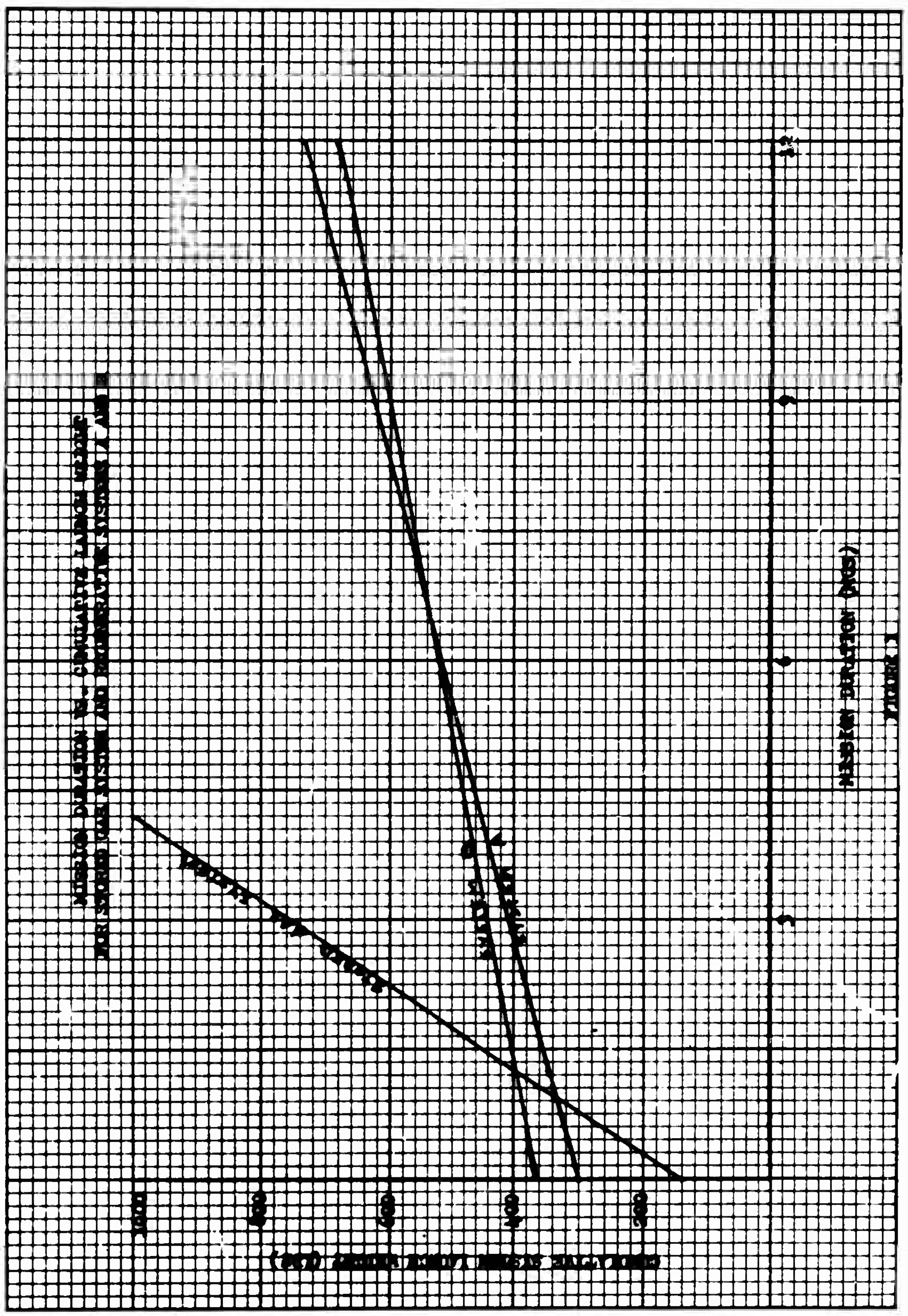
When processes, techniques, and degrees of confidence are carefully examined, it can be determined that it is now possible to support men in a space environment for several weeks without resupply by combining various state-of-the-art techniques. The technology of most of these techniques has attained the necessary degree of confidence so that the researcher, considering subsystem integration reliability and leakage, can recommend the design of a highly reliable one-gas atmosphere control system with a launch weight expenditure of approximately 350 lbs. per man for a three (3) week mission time. This system includes cryogenic oxygen supply, carbon dioxide removal, humidity control, and trace contaminant removal. Waste management and food supply are not included. The system does not allow for oxygen recovery; and removal of carbon dioxide, water vapor

and trace contaminants is accomplished by chemical absorbents. A leakage rate of 0.5 lbs. per man day is assumed. Total system weight vs. increasing mission time for a one-man vehicle is shown on Figure 1.

As vehicle mission time increases beyond thirty (30) days, regenerating atmosphere control processes becomes increasing attractive. The previously mentioned chemical-mechanical system for recovering oxygen becomes more attractive from a weight standpoint. There are two (2) primary chemical-mechanical systems to be considered. The first, or System A, relies on carbon dioxide reduction to methane and water and the second, or System B, depends on carbon dioxide reduction to carbon and water. In both Systems A and B, the water is electrolyzed to provide oxygen. Carbon dioxide is removed by molecular sieves, water vapor by silica gel, and trace contaminants and noxious odors by a catalytic burner and activated charcoal, respectively. System A includes hydrogen make-up since the methane is exhausted to space without processing to recover hydrogen. Figure 1 contrasts both systems for weight vs. mission time. A solar cell auxiliary power system at a weight penalty of 300 lbs. per kilowatt of power is assumed. A leakage rate of 0.5 lbs. per day is assumed. The processes included in the stored gas system and regenerating systems A & B are listed by component in Table 3. This listing is only suggestive of these systems and is not intended as an actual component list.

TABLE 3

Stored Gas System	Regenerative System A (Sabatier)	Regenerative System B (Bosch)
Supercritical Oxygen Storage Tank	Supercritical Oxygen Storage Tank	Supercritical Oxygen Storage Tank
Pressure Transducer	Pressure Transducer	Pressure Transducer
Oxygen Demand Valve	Oxygen Demand Valve	Oxygen Demand Valve
Vent Valve	Vent Valve	Vent Valve
Oxygen Partial Pressure Sensor	Oxygen Partial Pressure Sensor	Oxygen Partial Pressure Sensor
Total Pressure Sensor	Total Pressure Sensor	Total Pressure Sensor
Particulate Filters	Particulate Filters	Particulate Filters
Silica Gel Cannister	Atmosphere Circulation Fan	Atmosphere Circulation Fan
Atmosphere Circulation Fan	Catalytic Burner	Catalytic Burner
Lithium Hydroxide Cannister	Catalytic Burner Booster Pump	Catalytic Burner Booster Pump


MISSION DURATION VS. CUMULATIVE LAUNCH WEIGHT
FOR STORED GAS SYSTEM AND REGENERATIVE SYSTEMS A AND B
1000
800
600
400
200
CUMULATIVE SYSTEM LAUNCH WEIGHT (LBS)
STORED GAS SYSTEM
SYSTEM B
SYSTEM A
3
6
9
12
MISSION DURATION (HRS)
FIGURE 1

Stored Gas System	Regenerative System A (Sabatier)	Regenerative System B (Bosch)
Activated Charcoal	Activated Carbon Cannister	Activated Carbon Cannister
Atmosphere Processing System Pumps	Molecular Sieve Cannister	Molecular Sieve Cannister
	Silica Gel Cannister	Silica Gel Cannister
	Booster Pump for CO_2 and Water Vapor Removal Device	Booster Pump for CO_2 and Water Vapor Removal Device
	Coolant Fluid for Atmosphere Temperature Control	Coolant Fluid for Atmosphere Temperature Control
	Booster Pump for Coolant Fluid	Booster Pump for Coolant Fluid
	Molecular Sieve Selection Valve	Molecular Sieve Selection Valve
	Molecular Sieve Isolation Valve	Molecular Sieve Isolation Valve
	Silica Gel Selection Valve	Silica Gel Selection Valve
	Silica Gel Isolation Valve	Selica Gel Isolation Valve
	Gas Expulsion Valve To Space	Gas Expulsion Valve To Space
	Carbon Dioxide Reduction Reactor	Carbon Dioxide Reduction Reactor
	Methane Removal Unit	N/A
	Methane Expulsion Valve	N/A
	Electrolysis Cell	Electrolysis Cell
	Hydrogen Make-Up Storage Tank	N/A
		Carbon Removal Device

Although it was not pointed out in this table, special attention must also be given to the contaminant sensing and control problem in addition to oxygen recovery from carbon dioxide. This problem is not so apparent in short-term, high leak rate vehicles, such as Mercury. The use of a regenerating atmosphere control system, however, necessitates a low leak rate so that the quantity of stored gases required for make-up can be minimized. Since the low leak rate is necessary for economy of launch weight, the problem of contamination of the vehicle atmosphere by materials outgassing and by the occupants themselves presents a serious problem. Trace contaminant and noxious odor removal processes must be developed, together with an atmosphere sensor capable of both identifying and quantitatively measuring them. This is a special problem in itself, because of the present scarity of information on the contaminants, their sources, and the threshhold limit values for humans. There is also a problem in the design of an atmosphere sensor which is capable of determining the nature and concentration of all the contaminants which may enter the cabin atmosphere over a long period of time. This sensor must be small, lightweight, highly reliable, easily serviceable, and require low power.

Summary:

A considerable amount of analytical and experimental effort is required before the design of atmospheric control equipment for space vehicles can be put on a rational basis. This is particularly true for flight application of extended duration where partial or complete regeneration of atmospheric constituents is required. The following discussion is a summary of efforts required to gain information presently lacking.

1. The determination of atmospheric control breathing and pressurization gas requirements involves careful consideration of leakage rates and process component efficiencies. Realistic data on fluid leakage rates to be expected in typical vehicles are currently lacking.

2. The calculation of transient gas composition and pressure in a semi-closed or closed atmospheric control system requires analysis by computer programming. Such computer programs are urgently needed.

3. Studies of cryogenic fluid storage indicate the following:

a. Several types of fluid containers now under development show promise for space vehicle use. Data on the performance of these containers under zero-gravity conditions is required to permit accurate analysis.

b. Existing data on the thermodynamic properties of oxygen and nitrogen are only marginally adequate for the analysis of super-critical storage. Additional data are required to permit analysis of vessel operation under transient conditions.

4. Studies in the area of humidity control indicate the following:

a. Semi-permeable membranes appear feasible for water separation. Experimental verification is recommended in view of the attractiveness of such

materials for space flight applications.

b. The analysis of wat removal by adsorption in packed beds can be conducted along the general lines customarily used in chemical engineering practice. Detailed evaluation of sorber design methods is required for space vehicle applications where weight volume and power must be minimized.

5. A number of approaches to carbon dioxide removal appear feasible The following comments are pertinent:

a. The feasibility of the use of molecular sieves has been demonstrated for applications requiring regenerable adsorbents. Systems using these materials in applications where carbon dioxide is dumped overboard require the development of low-leakage valves sealing against the space environment. Experimentation is required to obtain design criteria for molecular sieve beds.

b. The removal of carbon dioxide by semi-permeable membranes may be possible. Experimental evidence compiled to date, however, shows that basically new membrane materials must be discovered before experimental verification of this method can be established.

c. The use of biochemicals such as organic amines for the adsorption of carbon dioxide appears attractive for long duration mission application. Experimental investigations must be conducted to prove the workability of this technique.

6. Several chemical methods for recovery of oxygen from carbon dioxide by catalytic reduction appear feasible. Effort is required in the integration of carbon dioxide removal and reaction processes.

7. Electrolysis cells of various configurations and utilizing basically different principles of operation have been shown to be workable under one "g" conditions. The workability of these cells under zero gravity conditions must also be demonstrated.

8. Data on trace contaminants are not adequate for system design from qualitative or quantitative viewpoints. Detailed study will be required for each application to determine expected contaminant types and generation rates.

9. The development of compact, accurate atmosphere composition sensors with long life expectancies is urgently required.

DISCUSSION

MR. THOMPSON: At this time I will try to conclude the talk by discussing several areas in which there is commonality between regenerating the atmosphere in a vehicle and on a planetary site base, and some of the differences. The main difference, certainly, between the researchers and the engineers performing research on these processes right now for vehicles is that material conservation in the space vehicle is at a premium. This may or may not necessarily be so at the planetary base, and for this reason sometimes you do encounter, if not resistance, reluctance, of the chemical engineer or the biologist to discuss or consider this as a serious problem until at least the vehicle systems have been refined. The commonality between the systems required for both vehicle and the bases is that the power utilization and leakage are both at a premium in either case and in both areas is probably the greatest amount of research required in order to optimize the regenerative system either from weight or power considerations.

MR. GREEN: There are interesting geological aspects of recovering water from atmospheres, both abundant materials coming out of fumaroles as water vapor followed by carbon monoxide or carbon dioxide. I would like to ask a question. What are the relative efficiencies of a silica gel versus electrolytic?

MR. THOMPSON: The molecular sieve during the absorption cycle would be the more efficient.

QUESTION: Much more?

MR. THOMPSON: Oh, I would say so, yes. I would say silica gel, because there is more known about it at the present time, at least for water vapor absorption. But that is the only reason I could give.

DR. EDSON: The spacecraft, Apollo type, is going to be 5 psi and the space suit is 3.5 psi, and the space ship or the lunar base is 7 or 7.5 psi, and the astronauts will be going back and forth frequently between these different levels and different atmospheres, what about the consequences?

MR. THOMPSON: Well, of course the obvious consequences to the crew members in transit, is going from such an atmosphere to reduced pressure. For the individual there would be need for a pressure vessel in which a person could out gas the hydrogen or gases from your system before proceeding in the oxygen atmosphere, or debending. In going from the lower pressure to higher pressure, there will also be a period of time in which he would have to acclimatize himself to pressure.

MR. MALCOLM: I might say this is a problem and even if going from a two to one reduction and four hours free breathing time, the experts can't guarantee we aren't going to have symptoms of disturbance. The School of Aero Space Medicine has just looked at

this problem. They found that going from 5 psi to the 3 psi of a space vehicle operation, provides very little problem as far as the possibility of bends is concerned. The problem might occur at even 5 psi if you use nitrogen-oxygen, and certainly from 3 psi to 5 psi down to 3, there would be a possibility of bends.

MR. MALCOLM: On preselection of personnel, I don't think that just with the Navy they had observed divers and all of a sudden they got bends.

MR. THOMPSON: Because the criteria, one of the criterions is age and that increases the probability, but there are people who are predisposed initially to getting bends, and there are other people who just don't get them, and this will be part of the selection criteria.

WASTE WATER RECOVERY IN EXTRATERRESTRIAL ENVIRONMENTS

James E. Malcolm

Abstract

A review of current developmental processes for the recovery of water from human wastes is presented. In the review, the basic process principles are discussed and flow diagrams are included depicting the steps in the processes. This discussion points out that all the processes considered are still in the developmental stage except those for recovery of water from atmosphere management systems. It is concluded that system optimization depends on the particular extraterrestrial problem into which it is to be integrated, and that development of design data will require operation of integrated model systems.

Previous status of the art reviews of water recovery processes have been published (1), (2), (3), (4), (5), (6), (7), (8), (9), (10). This review is directed, however, to the elucidation of the basic process principles and evaluation of the engineering feasibility of the more promising water recovery processes considered to date.

Water recovery in extraterrestrial environment may be accomplished by a number of different processes, and the choice of the process to be applied depends in part on the local environment concerned. For example, in unpowered trajectories, unless an acceleration force field is produced by rotation of the vehicle, the environment in the vehicle will be gravity free, and waste collection techniques will be required which operate zero g. Consequently, the waste collection and water recovery processes vary in technological difficulty with each possible situation.

One parameter not considered as critical in prior assessments is the magnitude of recovery effort required, or in other words, how many men are to be supported by the water recovery system. The interest of the Working Group on Extraterrestrial Resources includes the exploitation of extraterrestrial land mass resources, wherein habitation by man may be in groups of twelve or more. In support of such groups, the water recovery problem will admit techniques considered conventional in the earth environment. For example, aerobic digestion of contaminated waste water followed by filtration, sterilization techniques, etc. could be applied. Use of aerobic digestion as a process step has been included in a 30 day test demonstration conducted by NASA, OART and the Boeing Company, Seattle.

In smaller systems, however, such as spacecraft, integration of such a process may not be feasible, and the problem of waste collection becomes more

critical, since large quantities of "working water" for washdown, etc. are not permissibie because of the necessity to minimize weight. Also in contrast to the problem of water recovery in extraterrestrial bases, for short flights reclaiming of water from waste becomes non-competitive with water and waste storage, at the point where weight of processing equipment and power conversion exceeds that of the water consumed and waste stored.

For an overall systems evaluation, not only must the number of personnel to be supported be known, but the interfaces and interrelationships with other links in the closed system providing the extraterrestrial environment must also be determined. Because of this, it is virtually impossible to state the relative merits of the various systems without specifying the application envisioned, hence only qualifying remarks can be presented pointing out merits under differing conditions of application.

The techniques for waste collection and handling prior to water recovery will also vary with the gravitational environment, and the limitations on the overall system weight and volume. These techniques will not, however, be included in this discussion.

Following is a brief digest of the problem of water recovery in extraterrestrial environment and description of the unit operations considered most feasible for engineering application in the current status of the art.

Classically, the problem in vehicle systems has been categorized as:

Water recovery from the atmosphere.
Water recovery from urine and wash water.
Water recovery from solid wastes.

The first problem is relatively simple compared with the others and ties in closely with atmosphere and thermal control. Some techniques required are simple but would require expending activated charcoal for odor removal, and filter elements for solid particulate removal, which could possibly over a long period of time engender a logistical burden. Techniques for atmospheric water recovery are cited in Mr. Thompson's discussion of dehumidication.*

Water recovery from urine and wash water will require considerably more complex system than for atmosphere recovery. Urine water recovery has been the subject of considerable investigative effort. We cannot say that there are no satisfactory technical approaches to this problem, but certainly all aspects have not been proven out.

One rather basic point is that we are not certain concerning the significant criteria in defining purity of water with respect to unconventional processing techniques. For example, is virus contamination a hazard in low temperature vacuum distillation? This is the type of problem which is recognized in the AMRL study program.

* See Page 275 of these proceedings.

Although some of the processes here discussed result in sterilization of recovered water, their application may prove limited by the weight associated with the process energy required.

Water recovery from solid wastes is considered the most difficult and presents problems in materials handling and odor control.

In all of the processes discussed to accomplish water recovery, aside from terrestrial application of the activated aerobic digestion of solid and liquid wastes, there have been no occasions for practical applications; therefore, the state-of-the-art is reflected in the laboratory and pilot demonstrations to date.

Engineering data, i.e. weights of process equipment, capacities, energy requirements, and general reliability and maintenance requirements are generally speaking, known only in part based on the laboratory and pilot demonstrations; hence, it does not appear desirable to classify any of the processes reducible to practice in the current state-of-the-art insofar as extraterrestrial application is concerned. Even in the case of aerobic digestion of wastes, this is also the case since only one pilot demonstration of this system as a step in a system simulating space application has been reported.

One significant observation is that test demonstrations have not been for the most part sufficiently long to develop reliability criteria to the extent necessary to permit system design and selection without the necessity to undertake extensive proof tests; in addition to the fact that in many of the proposed processes, all parameters have not been completely searched out, such that all materials requirements, equipment weights, and even power requirements (or thermal loading of the system) are not completely defined and supported by engineering documentation.

This general evaluation must not be interpreted to mean that there are not a number of approaches of promise, which may be considered in developing concepts of integrated life support systems, since it may be seen from the background literature that examples of laboratory demonstrated operations are in abundance.

Activated Aerobic Digestion of Wastes

Activated aerobic digestion of wastes, or activated sludge processes designates a collection of the most popular terrestrial processes for biological digestion of human wastes. These processes have the common characteristic of using preformed biological flocs in an aerated system to contact, and floculate liquid wastes input, and convert the organic wastes to inorganic forms. A conventional terrestrial process is shown in Figure 1. This process depends on the chain of biological feeding steps, first involving bacteria and molds which feed directly upon the waste elements, and which in turn produce cellular material upon which protozoa feed, and which in turn may be consumed by lower metazoic forms. In the aeration of the wastes in contact with the returned sludge, two biological process stages are involved. One is the clarification stage, in which the colloidal and dispersed organics are absorbed on the surfaces of the sludge floc. This stage is rapid in accomplishment, whereas the second

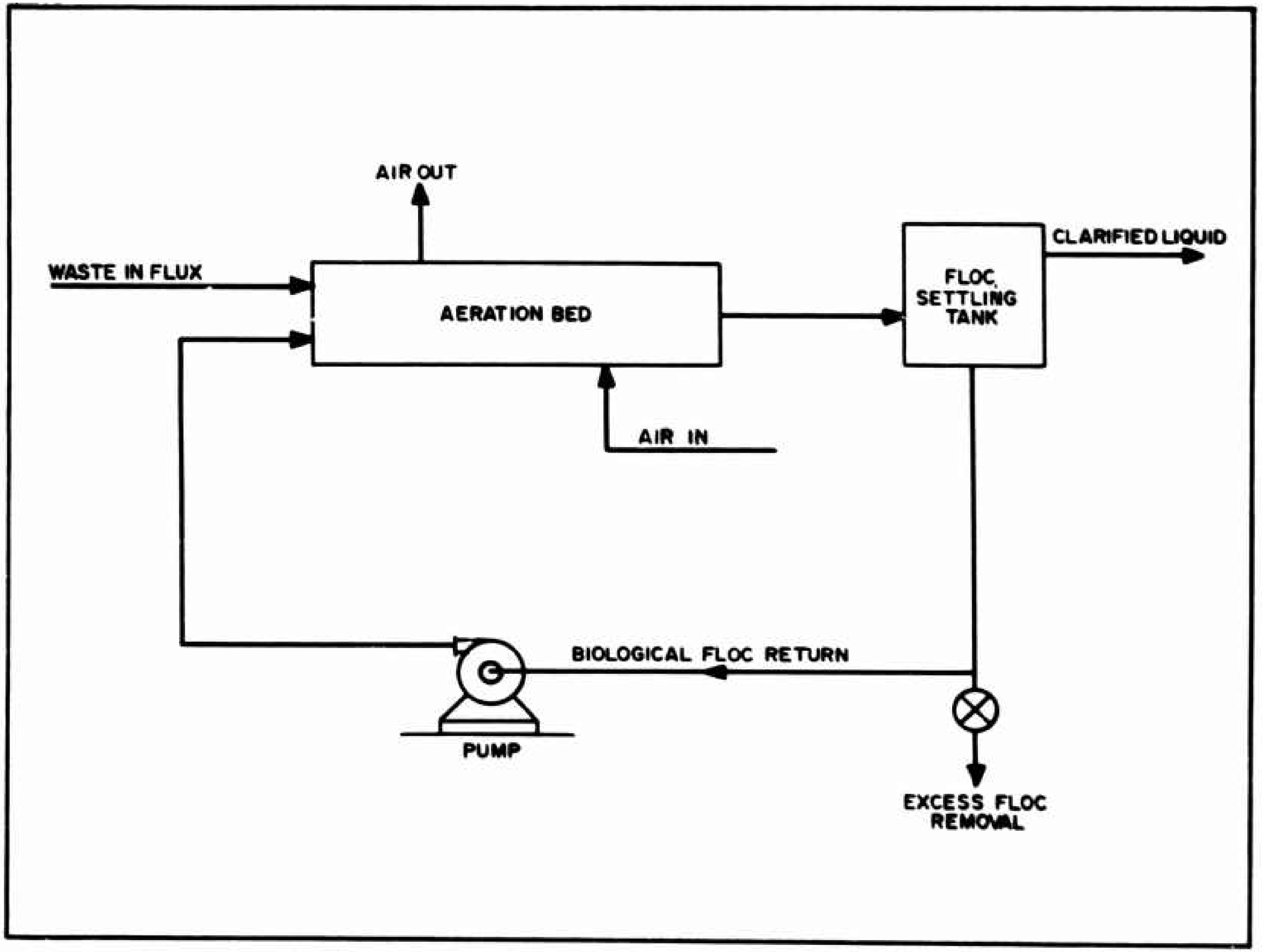


FIGURE I - AEROBIC ACTIVATED SLUDGE WASTE TREATMENT, TERRESTRIAL APPLICATION

stage requires four to eight hours of aeration, and is the stage involving the actual waste assimilation by the active sludge elements. The sludge concentration in the aeration process may vary from 1.5 to 2.5 gms/liter, whereas, after separation from the clear effluent in the settling tank the sludge concentration will be about 10 gms/liter. As noted in Figure 1, the net growth in sludge is removed as sludge waste from the sludge recycle stream. As indicated by "aeration" this process consumes oxygen and produces carbon dioxide, thus in a closed ecology provision must be made for the oxygen demand and carbon dioxide removal or absorption. The low sludge concentration as indicated in terrestrial systems may be interpreted to mean that the system must encompass a large working water capital, thus it appears limited to application in land based operations of advanced generations. In addition, post treatment including concentration of the sludge, and incineration, or desication of the sludge will be required.

Vacuum Distillation

Vacuum distillation is a technique for recovery of water from solutions comprising solutes such as urea which undergo thermal decomposition. For recovery of water from human wastes, distillation temperatures should not exceed 37°C in order to avoid hydrolysis of urea to form ammonia. The distillation system pressure must then not exceed 0.062 terrestrial atmospheres. At this low pressure the volumetric vapor flow rate is high compared to that at atmospheric pressure and hence the vapor ducts must be adequately designed.

Because of liquid entrainment in the water vapor, provision must be made for sterilization or filtration of bacteria and possibly solids entrained. In this process, as well as the combination of vacuum distillation and vapor phase pyrolysis described later, thermal energy must be added to the calandria-evaporator and absorbed from the condenser. Figure 2 shows a schematic diagram of a vacuum distillation system. A variation of this system shown in Figure 3 involves the use of thermoelectric elements. (11) In such a configuration, heat is drawn from one side of a battery of elements through individual semiconductor cells to the warmer side under the influence of electric current flow. One side of the "battery" forms the calandria or evaporator and the other the condenser. Since such a device furnishes more heat to the warm side than absorbed in the cool side, supplementary cooling must be provided at the 37°C thermal level.

The vacuum distillation systems could be designed for either batch or continuous operation. It must be noted that a waste residue must be removed from the evaporator, and that this residue will comprise water loss, unless is is subjected to further processing. Tendency to foul the evaporator with deposits is one factor limiting the degree to which the residues may be concentrated. Some batch systems have been fabricated in which disposable plastic liners have been used to prevent deposits in the basic unit. Loading of these units requires manual operations, however. Removal of non-condensible gases is a problem in continuous processes.

Another variation of vacuum distillation is incorporation of vapor phase compression (12) as shown in Figure 4. Here the principal components are a

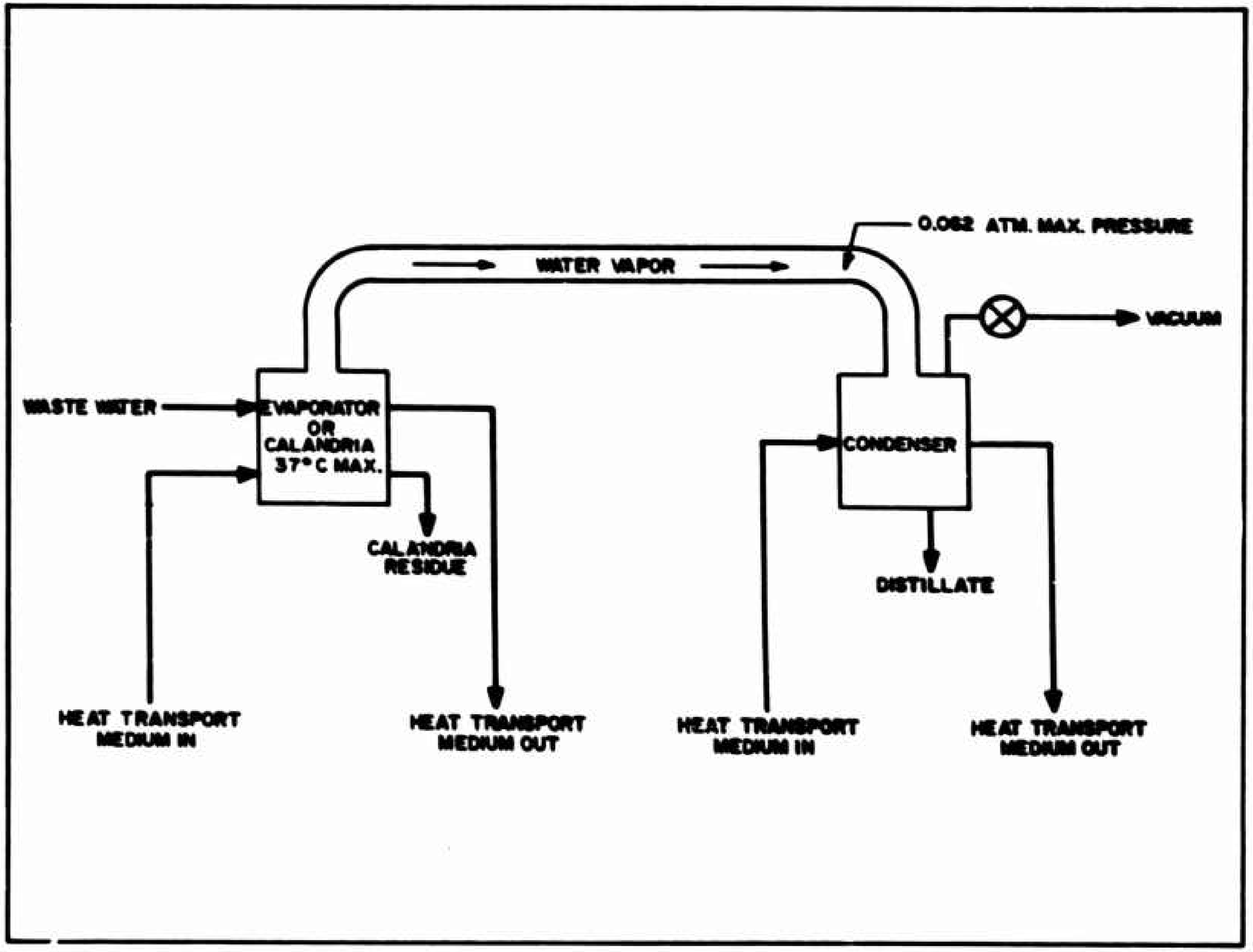


FIGURE 2 - WATER RECOVERY BY VACUUM DISTILLATION

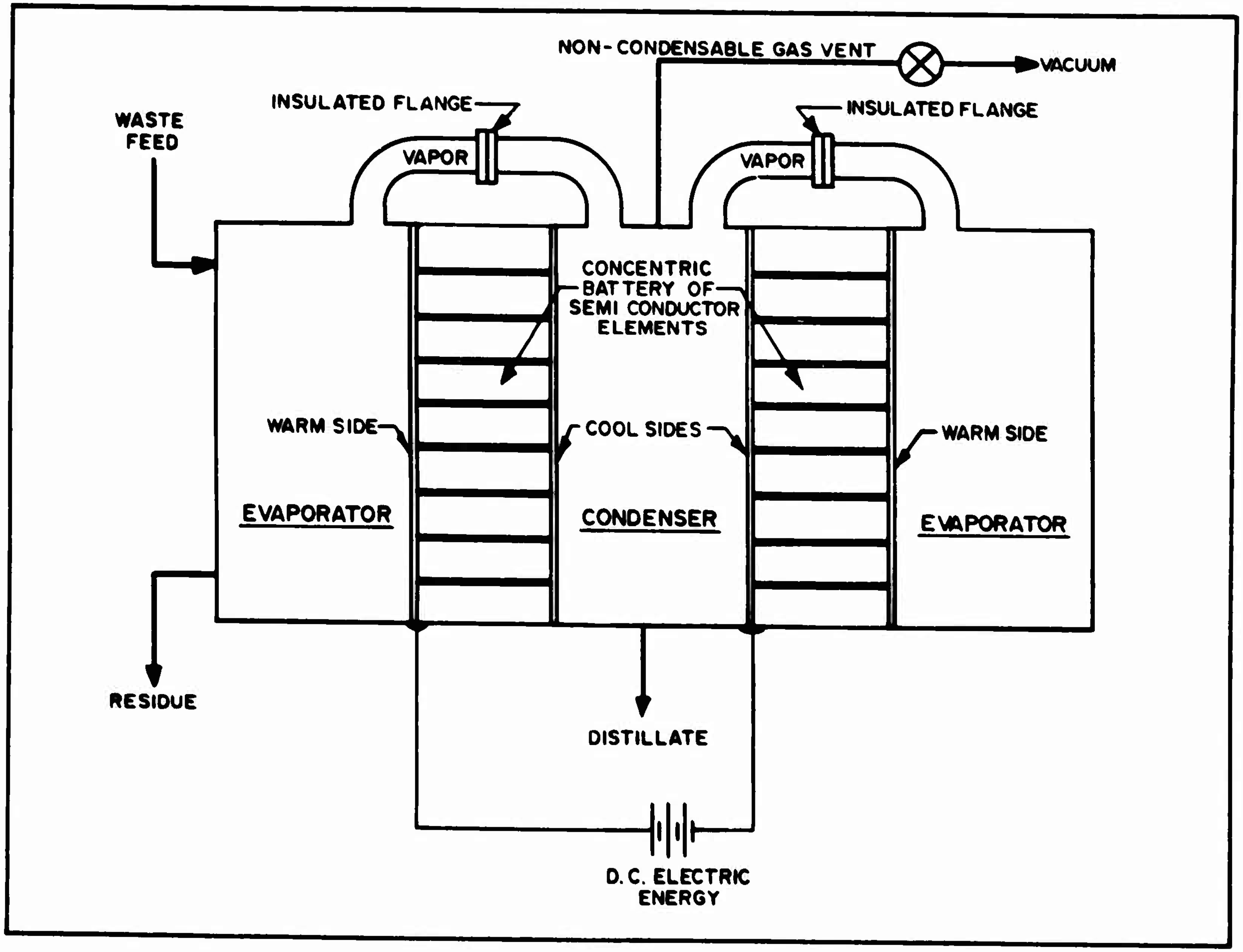


FIGURE 3 - SCHEMATIC THERMOELECTRIC LOW PRESSURE STILL

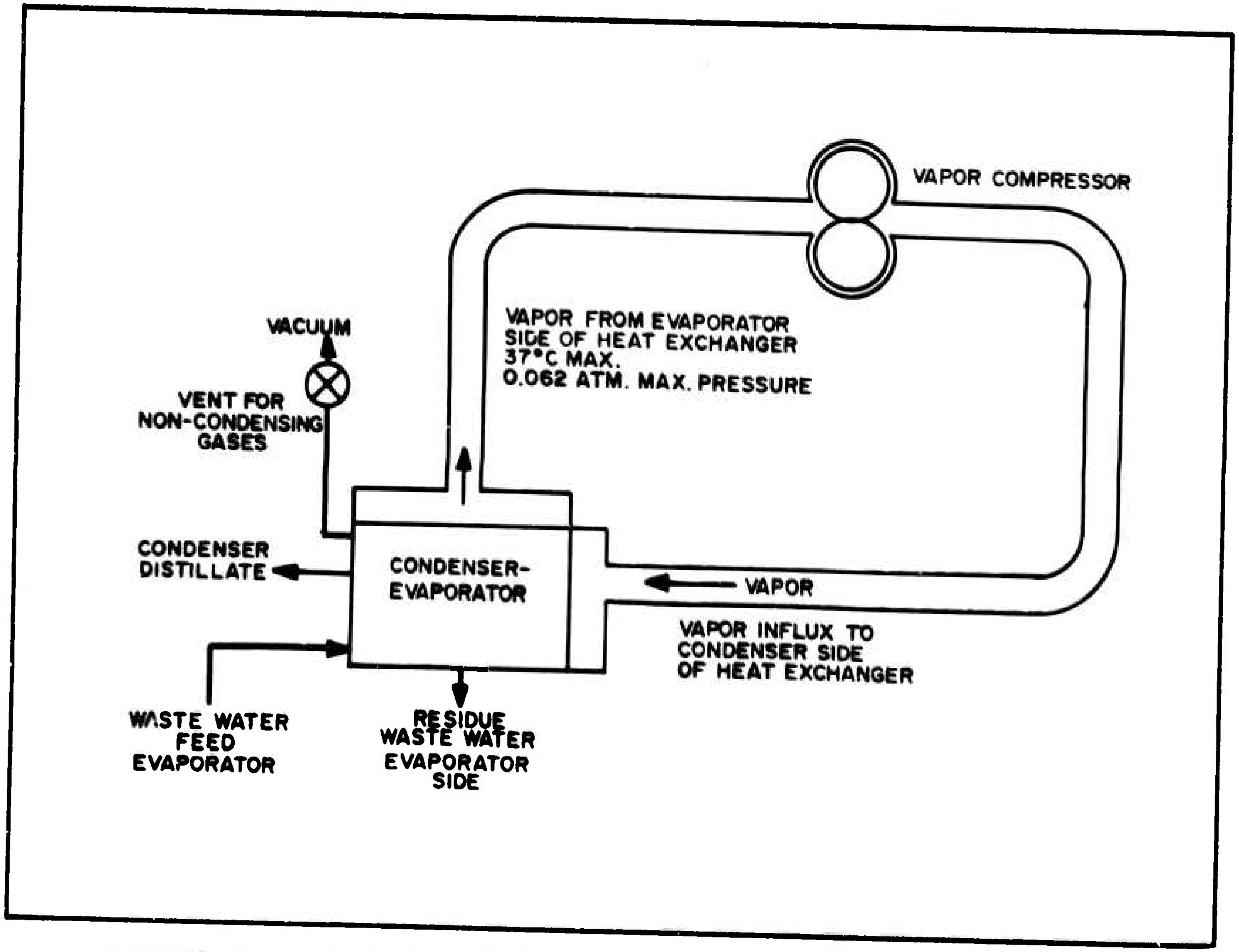


FIGURE 4 - VAPOR COMPRESSION DISTILLATION WATER RECOVERY

heat exchanger and a compressor. Waste is fed to the evaporating side of the heat exchanger, evaporated at about 25°C to a residue of about 10% of the original volume. The vapor is drawn-off by the compressor, compressed adiabatically with a temperature rise to about 35°C. In this process the thermal energy released on condensation of the vapor is used to evaporate the distillate.

Batch operation has been demonstrated in devices designed for zero gravity operation.

Vacuum Distillation With Pyrolysis Of Vapor Stream

In vacuum distillation with vapor catalytic pyrolysis (Figure 5) liquid wastes or a slurry of liquid and solid wastes are concentrated by distillation at a moderate temperature, ca. 40-45°C under a vacuum of about 0.079 atmospheres. Under these conditions, decomposition of urea is low, i.e. the hydrolysis: $CO-(NH_2)_2 + H_2O \longrightarrow CO_2 + 2NH_3$ is not extensive. Some ammonia is, however, released; hence, to avoid objectionable odors, elimination of ammonia is required. This may be accomplished by catalytically oxidizing the ammonia. To do this, air is bled into the distillation calandria-evaporator at a rate of about 40 liters per kilogram of water reclaimed. The air and water vapor are passed through a heated Pt-10% Rh catalyst at ca. 1250°C to oxidize any ammonia vapor, $4NH_3 + 3O_2 \longrightarrow 2N_2 + 6H_2O$, formed in the calandria. Some of the ammonia may be oxidized by the overall reaction, $4NH_3 + 7O_2 \longrightarrow 4NO_2 + 6H_2O$, from which nitrate ions are formed in the distillate or water recovered. The extent of the formation of the nitrate ions is, however, insignificant under the proper oxidation conditions. In low pressure distillation there is always the possibility of some liquid carry-over with the distillate vapors, and since at 40°C there is no sterilization of bacterial or viral elements, the catalytic oxidation temperatures provide for the vapor sterilization, in addition to the oxidation of ammonia.

The water vapors are condensed by means of a heat exchanger and the non-condensible air is pumped out of the collection vessel, or bled to outer space.

The nature of this process lends it conveniently to batch operation. The removal and disposal of the calandria residue presents a problem, and could require considerable development of auxiliary equipment. For example, problems with this residue could justify handling solid wastes by incineration.

The above process has been investigated extensively in the laboratory and the U. S. Naval Crew Equipment Laboratory (ACEL) (13) has operated an engineering demonstration model. Variations of the process have also been studied (14) wherein activated alumina was used in lieu of the Pt. 10% Rh catalyst, at a substantially lower temperature.

In the ACEL demonstration model, Okomoto (15) reports a 0.644 KWH electrically generated thermal energy input per kilogram of water reclaimed. Though some heat exchange was effected between the hot vapor effluent from the catalyst matrix and the incoming vapors, cooling water was used for the

condensation of vapor. In extraterrestrial environment this cooling requirement would be met by mechanical cooling or provision for low temperature heat rejection into space.

Osmotic Processes

Osmotic processes stem from the fact that the transfer of solvent from pure solvent to solution results in a decrease of free energy. For example, if two containers are placed in a closed space, one containing pure solvent, and the other containing the solution composed with the same solvent, the pure solvent will migrate by evaporation, and condensation into the solution, where the solution has a lower vapor pressure than the solvent in the pure state.

The explanation of the mechanisms by which this decrease in free energy occurs is still subject to conjecture, however, the effect is well known. This effect is shown in the situation where a membrane permeable to the solvent and impermeable to the solute can be placed between the interface of solvent and solution. In this situation a migration of solvent to solution takes place and a pressure termed osmotic pressure is defined as the excess pressure which must be applied to the solution side of the semipermeable membrane to prevent migration of the pure solvent from the side of the membrane containing the pure solvent.

Extention of this phenomenon has been proposed and termed ultrafiltration (16,17) in which pressure is applied to a waste solution, contained by a semi-permeable membrane, to force water to migrate (reverse osmosis) through the semipermeable membrane, leaving the solutes concentrated on the pressurized side of the membrane. Figure 6 shows such a system.

Problems in the application of such a system include fabrication of a durable membrane, permeable to water yet capable of rejecting solutes. The membranes evaluated thus far appear so permeable to urea (60 to 80% removable per pass) that either pre-treatment for removal of urea or cascading of ultra-filtration systems will be required. Pressures of 135 atmospheres have been used in laboratory demonstrations, wherein treated urine (urea having been hydrolyzed, and ammonia converted to ammonium citrate) was circulated over a cellulose acetate membrane, giving initial through flow rates of ca. 0.6 cc hr^{-1} cm^{-2} membrane area. In laboratory demonstration, this rate was noted to decrease as much as 50% in a 24 hour period.

A variation of reverse osmosis is thermo-osmosis, a membrane permeation technique wherein a temperature gradient across a semi-permeable membrane is applied with the higher temperature on the solution side to provide the driving force for the migration of solvent to the pure solvent side of the membrane.

In laboratory demonstration equipment, reduced pressure has been applied on the filtrate side of the thermo-osmotic membrane. Ca. 0.22 cc Hr^{-1} cm^{-2} filtration rates have been attained.

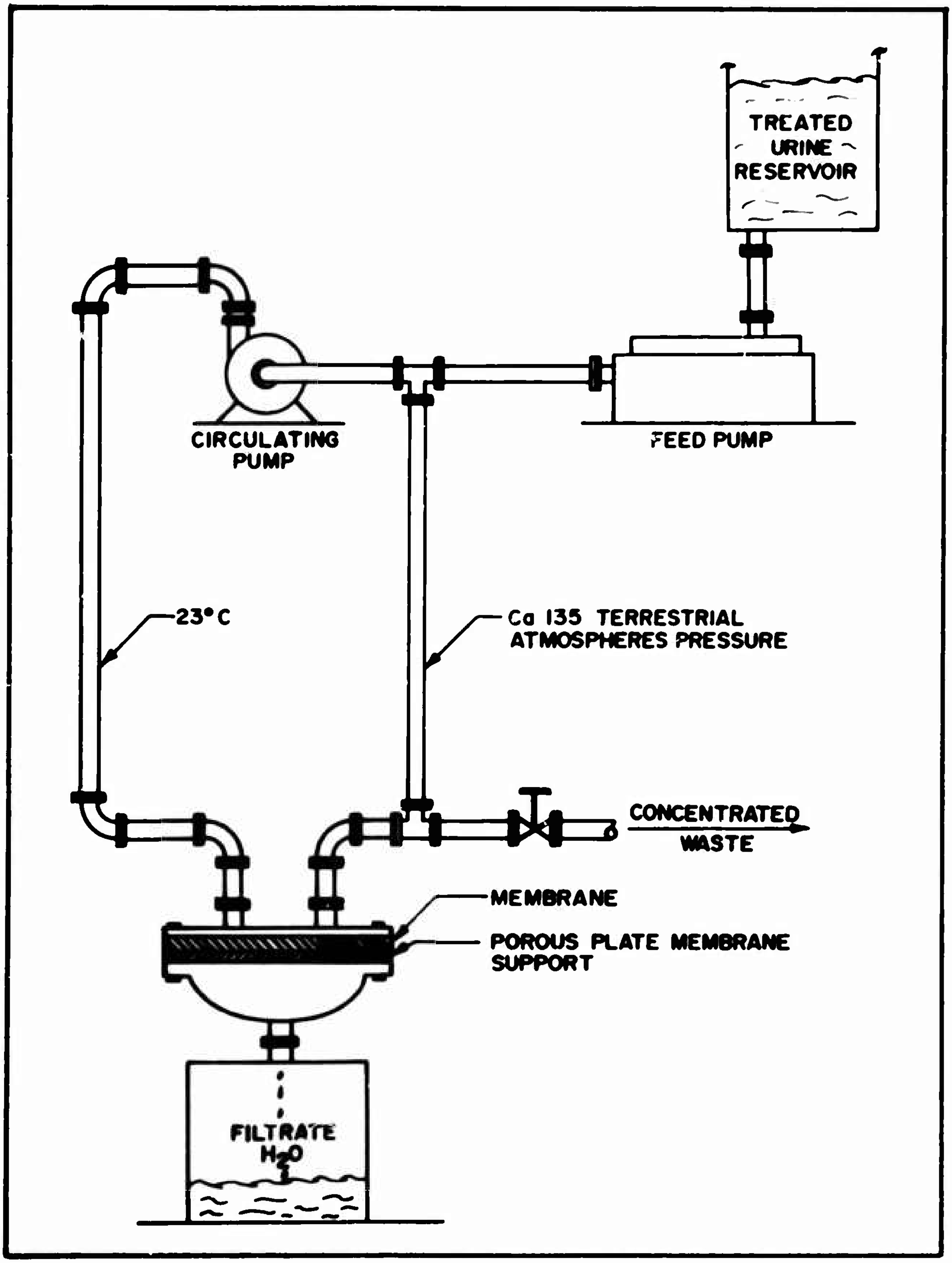


FIGURE 6 - ULTRAFILTRATION CELL

A system utilizing ultrafiltration is currently under investigation by the NASA Langley Research Center. In this system the pretreatment would consist of electrolytic denitrofication of urine which also sterilizes the input to the ultrafiltration stacks. The ultrafiltration unit could recover water from dilute detergent wash water solution directly without the denitrofication step.

Electrodialysis

Electrodialysis is the process utilizing electromotive force to drive ions in solution across electrically conductive semipermeable membranes (18). Paired membranes are used, one in essence permeable to cations only and the other to anions only. In the presence of an electric potential, which provides the driving force, cations (positive ions such as K^+, Na^+ etc.) pass through the cation permeable membrane, and the anions (negative ions such as Cl^-) in equilibrium with the solute cations pass through the anion permeable membrane, as seen in Figure 7. The membranes in addition to being impermeable to water (except for the endosmotic migration of water with the ion transport) are also impermeable to urea which is not ionized in water solution and therefore not driven by the electromotive force applied to the electrodes. To apply the electrodialysis process for urine recovery it is then first necessary to remove or hydrolyze the urea. Hydrolysis of urea using the enzyme urease proceeds as:

$$(H_2N)_2\,C = O + 2H_2O \xrightarrow[\text{Urease}]{\text{Enzyme}} (NH_4)_2 - CO_3$$

The formation of NH_3 and CO_2 from the ammonium carbonate under thermal stress may pose some additional problems. Carbon dioxide may be passed off to the atmosphere control system, provided the ammonia (NH_3) is removed. Suppresion of NH_3 may be accomplished by adding hydrochloric acid to form NH_4Cl or by pyrolytic oxidation of any liberated NH_3 as discussed previously. The enzyme, urease, is lost from the system with the final residue from the electrodialysis cells, and hence is an expendable in the process. Urease may be added to urine at a ratio of 2 gms per liter of urine, to hydrolyze 95% of the urea in a 12% solution of urea in water in two hours at about 25°C. Some urea and other non-ionic organics remain such that an additional pretreatment is required. About 200 gms of cocoanut charcoal absorbant per liter of urine appear necessary to remove most of the remaining urea and urease in about 1/2 hour contact time. An alternate treatment is the use of about 400 gms of the cocoanut charcoal per liter of urine to remove urea as effectively as the sequence of hydrolysis and charcoal absorption. With complete urea removal by absorption on charcoal alone, a lower ion concentration is present in the solute because no ammonium carbonate is generated in the process of absorption. The lower ion concentration in the electrodialysis process where charcoal absorption is used as the pretreatment is preferred, from the standpoint that the lower the ion concentration to be removed the lower the endosmotic water loss (through water migration with the ions transported through the ion permeable membrane). Also, it has been found that after the electrodialysis step where hydrolysis of urea is the initial step, clean up, either charcoal absorption, or

deionization is required. In addition to endosmotic water losses, polarization losses may occur if the critical current density is exceeded, i.e. if the membrane transfer rate exceeds the ion migration rate in solution, water will be disassociated and OH^- and H^+ will be transported through the membranes.

It has been assumed that the charcoal absorption bed can be regenerated by heat and the vapor desorbed compounds can be disposed to space, such that the charcoal may be used repetitively for removal of the non-electrolyte (18), however, fouling of the charcoal may prove the case over extended time.

A variation of this process involves the use of a complexing agent in the urine pretreatment. A complexing agent is added to the urine collection container and serves to remove the urea as a precipitate and to maintain sterile conditions within the container. The complexing agent is an expendable item and its requirements are approximately 8 grams per liter of urine. The urine is filtered to remove the precipitate, and then is pumped through activated charcoal to remove the residual organic contaminants. Approximately 80 grams of wet charcoal are required per liter of urine. In the current state-of-the-art the charcoal absorbant is an expendable.

After pretreatment the urine is essentially salty water, i.e. consists of inorganic ions only in solution. Recirculation through the electrodialysis cells is continued until the level of disolved solids is reduced to about 200 ppm, as determined by continuously monitoring with a conductivity probe. The waste stream from the cells carries off the salts and about 5% of the input water. Where wetted charcoal absorber-units are used, this would represent total losses. Vacuum regeneration of absorbers would incur additional water loss from the absorbers. Flow of the waste stream is energized by ion movement in the electric field across the dialyzing membranes, hence no pumping is necessary to discharge the wastes.

Following the electrodialysis of the ionized constituents of urine, requiring several passes through the system, the demineralized water may then be passed through an ultra-violet radiation column to clean up any residual bacteria prior to return to storage. Such an arrangement is diagrammed in Figure 7. It does not appear that this process would be suitable for a waste product containing suspended solid matter.

Sublimation

Sublimation, freeze drying or lyophization is the evaporation of water directly as a vapor from frozen waste (19). The first step is freezing of the waste followed by sublimation. This process must be carried out below the triple point of the waste solution, that is under condition of pressure and temperature at which there is equilibrium between the solid and vapor state only. (The triple point of water is 0.01°C, or ca. 0.06 terrestrial atmospheres pressure.)

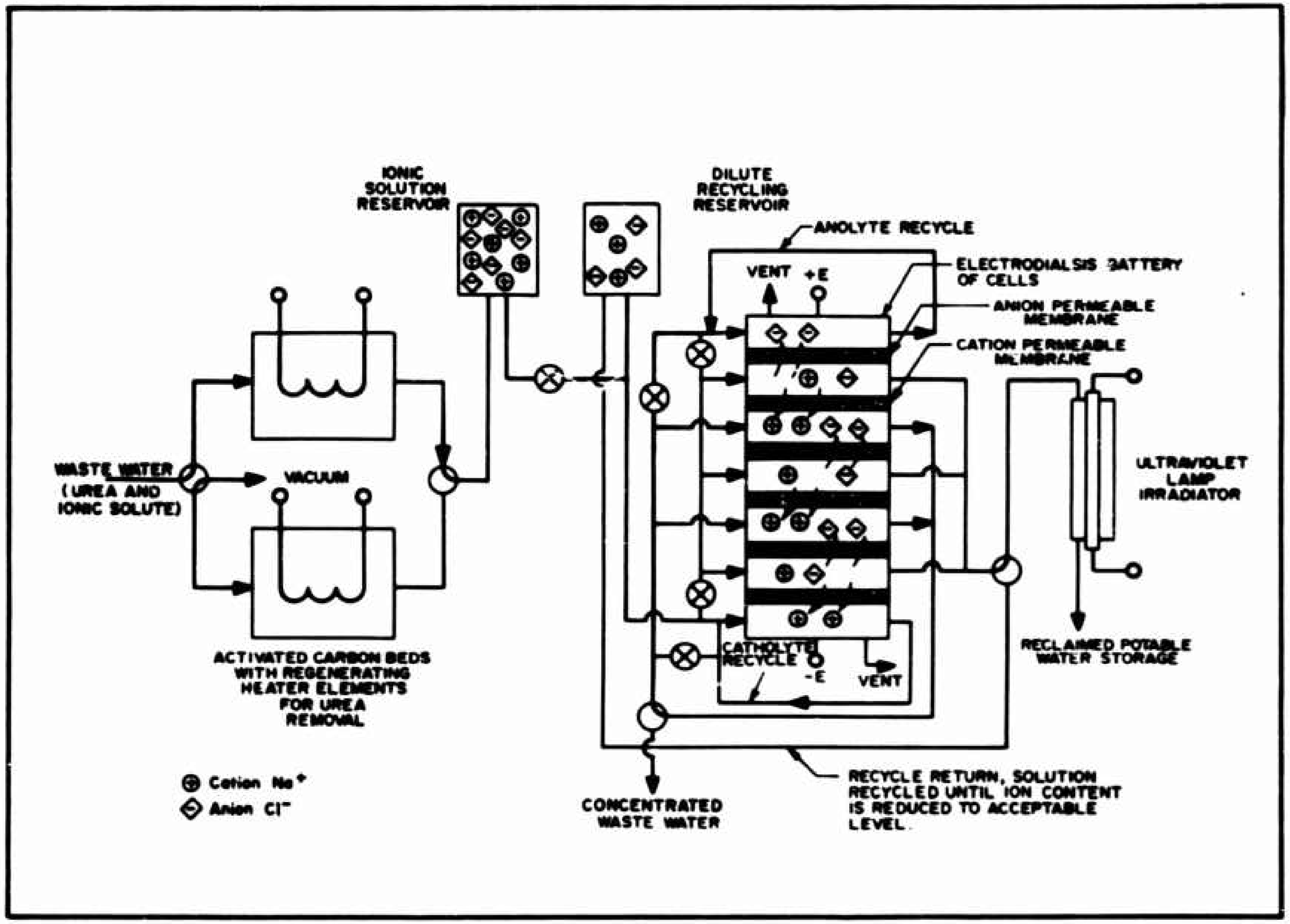


FIGURE 7 – SIMPLIFIED DIAGRAM OF ELECTRODIALIS SYSTEM FOR WATER RECOVERY

In gravity free environments the separation of solid and vapors is more favorably accomplished than separations of liquids and vapors. The solid residues from sublimation have been reported to be inoccuous and easily disposed of. However, the low pressures of operation require large cross section area ducts for vapor flow and larger areas for transport of the heat of sublimation and removal at the condensing surface, than in liquid to liquid heat exchangers. Heat must be admitted at a controlled rate in order to avoid melting of the solid at the heat exchanger interface. (i.e. to avoid high thermal gradient in the solid being sublimated.) A schematic diagram showing the sublimation phase of this recovery process is shown in Figure 8.

Electrolytic Processes

Laboratory demonstrations have been made of direct electrolytic sterilization and clarification of human wastes, in which the active mechanism is electrolytic oxidation (20, 21). In addition, biochemical fuel cells have been proposed in which electric energy is derived from waste oxidation. It has also been proposed to integrate waste electrolytic products of hydrogen and oxygen into a hydrogen-oxygen fuel system or to couple the electrolytic step with a fuel cell, such that part of the electrolysis energy is recovered along with reconstituted water. Figure 9 shows such a system.

In this schematic, an acid electrolyte type is depicted, embodying a double ion membrane electrolysis cell. The membrane as shown in the diagram comprises a sulfonic acid fixed polymer structure. Hydrogen ions may migrate from one SO_3^- group in the membrane to the adjacent, providing for ion mobility. Although the ion membranes are of lower electrical conductivity than acid or caustic solutions used in electrolytic or fuel cells, thin membranes may be used which reduce energy loss due to ohmic resistance. The schematic diagram shows that the potential required for electrolysis is about twice that produced by the fuel cell. Since the object of the system is to reclaim water with minimum energy outlay, to utilize the energy recovered by the fuel cell, it might be necessary to use two cells connected in series electrically in order to upgrade the recovered energy level of a usable voltage.

Air Evaporation

For liquid wastes, the air evaporation process uses air as a carrier of vaporized water. The liquid waste is evaporated from wicks. In the adiabatic system, heated air (possibly from the equipment cooling loop) is passed over unheated wicks wetted by the waste. The non-adiabatic system incorporates heated wicks, such that the air is not appreciably cooled in picking up water vapor, as is the case in the adiabatic system. Water vapor in the air stream is then condensed in an air cooling loop. This system has been proposed where it can conveniently be used between an equipment cooling air stream, and the heat absorbing and rejection unit. Evaporating wicks become fouled with solids after time in service, and must be replaced at regular intervals. In one unit designed for aircraft use, ion exchange resins were used to deionize urine before feed to the wicks. In that system the exchange resin consumption was high, and recovered water proved as corrosive as raw urine. (22)

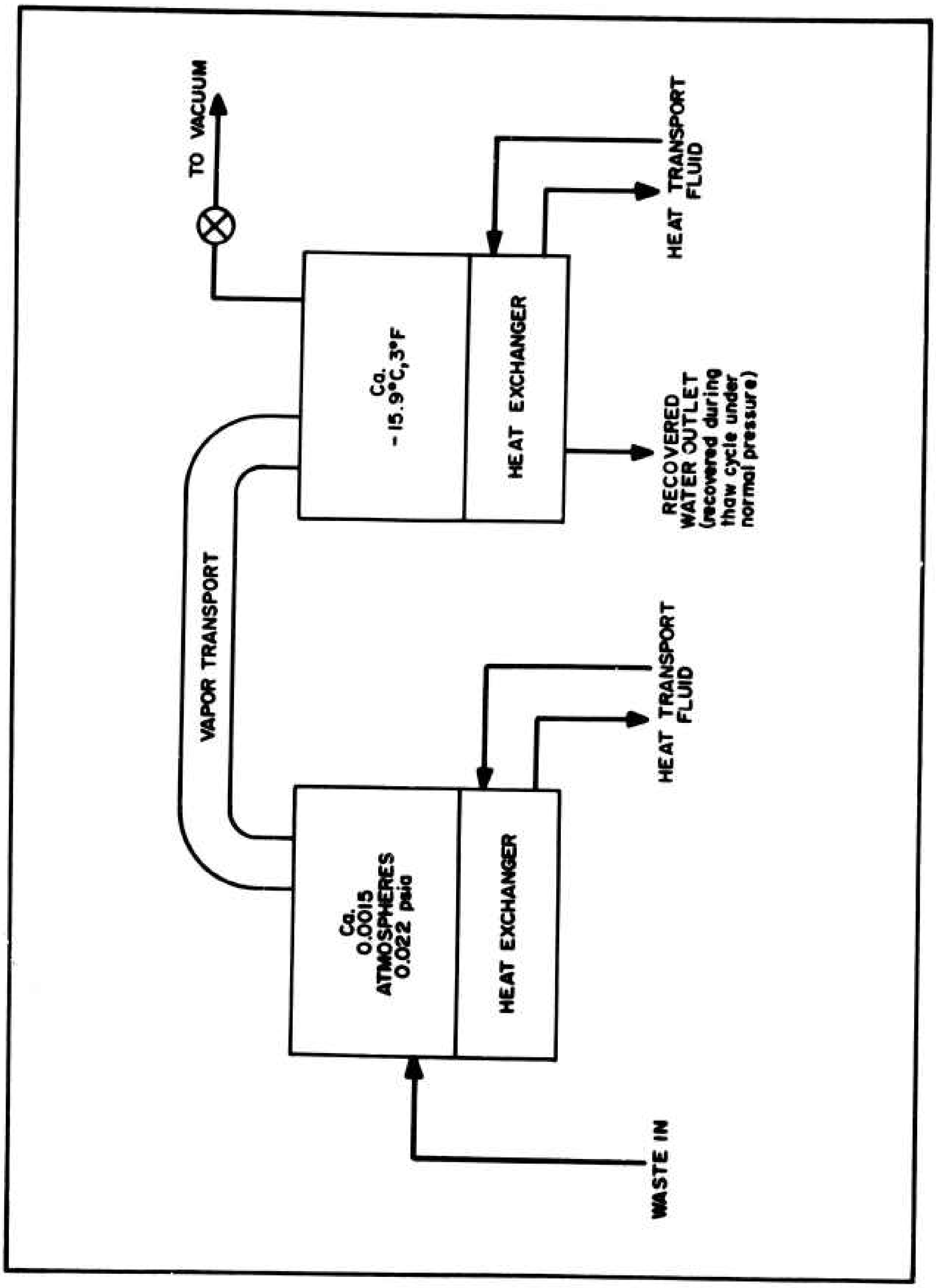


FIGURE 8 - FREEZE SUBLIMATION WATER RECOVERY

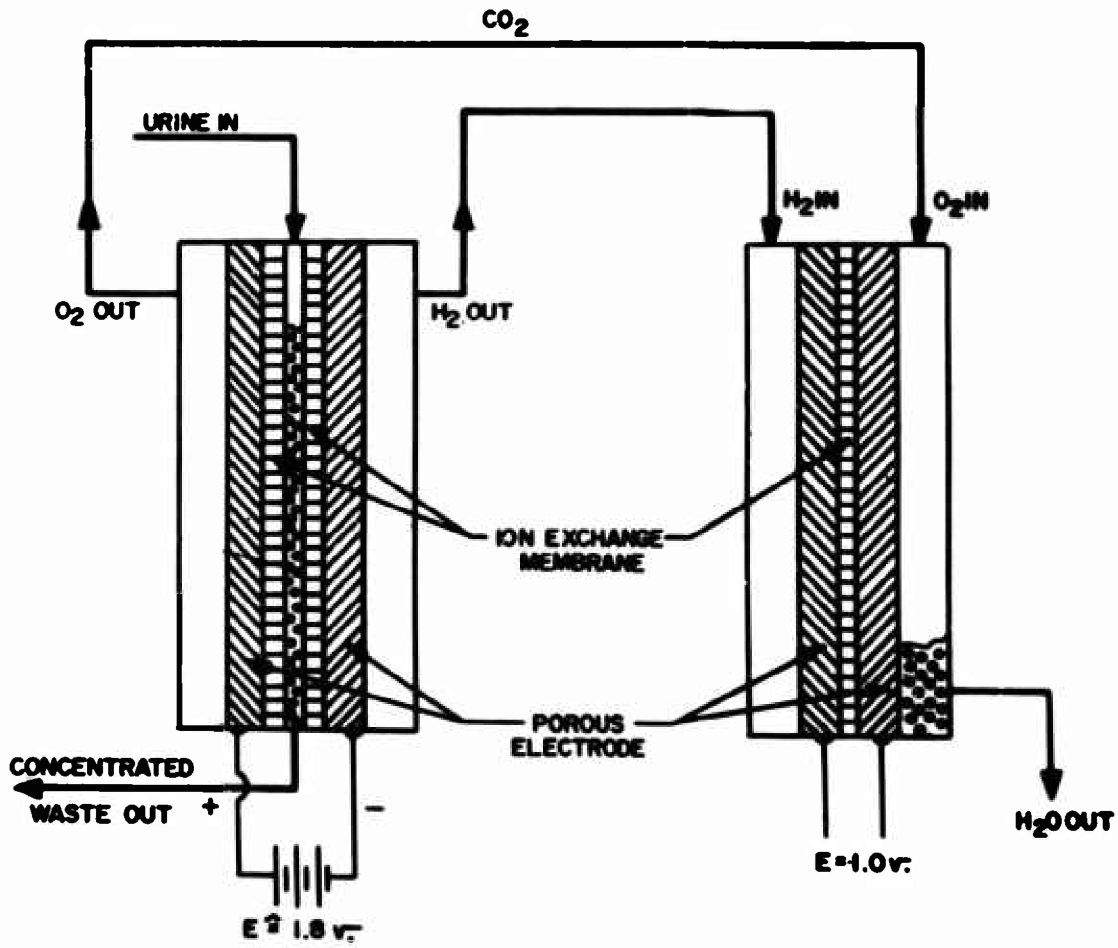


FIGURE 9 - ION-MEMBRANE ELECTROLYTIC CELL-FUEL CELL WATER RECOVERY SYSTEM

Solid Waste Water Recovery

The processes reviewed above concern primarily liquid wastes, or in some instances slurries (such as the aerobic digestion of human wastes) of liquid and solid wastes. For solid waste recovery, conditioning may be accomplished by aerobic digestion. Though a solid residue is derived from the active sludge drawn off from the systems, this appears to be more easily handled and stored than human fecal matter. The sludge residue could be air dried and incinerated to recover all water. Drying and incineration of fecal matter has also been suggested, however, odor removal from the drying air stream requires charcoal absorbers or the equivalent. Incineration of the solids (23) though productive of water, is at the expense of oxygen, both to combine with hydrogenous components and with the carbonacious to form carbon dioxide which results in a burden on the atmosphere management system. Thus, application of incineration can only be justified by evaluation of the integrated overall ecological support processes.

Since thought to date has been largely given to space flight and orbiting missions of relatively short duration, processes yielding the greatest return on energy input, that is those recovering water from liquid wastes and those incorporating the storage of solid wastes have been accepted as the most economical in many mission configurations proposed.

As a consequence, less specific information has been developed on water recovery from the solid wastes than from liquid wastes.

Parametrics of Systems

Figure 10 shows weights and volumes of equipments as currently developed and power requirements for the processing rates indicated. Remarks are included where available on the completion of the process, i.e. whether or not the demonstration included continuous collection of wastes, and processing through to the storage of potable water, or only comprised a step in an integrated system. Care must be taken in use of these parametrics since they are derived from systems designed to comply with specific situation requirements. For this reason the values cannot be numerically extrapolated to cover systems having greater or lesser capacity, since scale-up relationship are not necessarily linear. The data presented will have to be taken as representative of the currentweight and power requirements for specific designed systems.

Figure 11 presents for reference the water management requirements on a man-day basis. Any statement of man-day requirements for nutritional and waste disposal elements can only be arbitrary in that man's requirements vary according to the individual and the stress to which the individual is exposed. These parametrics are therefore range estimates of the anticipated requirements in extraterrestrial environments.

System	Fixed Weight Kg	Fixed Volume M^3	Capacity liter/day	Peak Power Watts	Energy Kw-hr/day	Expendable Weight kg/day	Yield %	
Electrodialysis	7	0.1	4	40	0.15	0.36	95	Currently reported performance by Fabricator (24)
Electrolytic Denitrofication and Ultrafiltration	ca. 30		5(a) 10(b)		1.6		90-97	Projected state of the art (25)
Vapor Pyrolysis Distillation	16.7(c) 16.7(d)	0.063 0.063	44 44	75	2.16(e) 1.68(f)		98 98	1000 Btu/h waste heat rejected to space with 4.5 Kg radiator required in addition to electrical energy (26)
Compression Distillation	23 23	0.07 0.06	18 18		2.00 1.50		95 95	Batch process, current state of the art. Projected continuous process. (27)

(a) Denitrofication
(b) Ultrafiltration
(c) Lunar
(d) Zero g
(e,f) Projected va.ues 720 and 249 w-hours, respectively

FIGURE 10 PARAMETRICS OF WATER RECOVERY SYSTEMS

PARAMETRICS FOR WATER MANAGEMENT

Requirements for Water:

Nutrition: 4.0 to 10 lb/man-day

Sanitation:

Austerity Basis: 3 to 6 lb/man-day

Simulated Earthside Basis: 30-70 gal/man-day

Requirements for Support Systems:

Urine: 2 to 6 lb/man-day

Processing:

Perspiration:

Airborne Removal: 2 to 8 lb/man-day

Wash Water Processing:

Austerity Basis: 3 to 6 lb/man-day

Simulated Earthside Basis: 30-70 gal/man-day

Fecal Water Recovery: 0.2 to 0.4 lb/man-day

WASTE CONTAMINANTS

Urine (3.2 lb/man-day basis)

Urea	0.07 lb/man-day
Salts, inorganic	0.055 lb/man-day
Organics, mis.	0.05 lb/man-day

Wash Water (5.0 lb/man-day basis)

Organics, soluble	5×10^{-3} lb/man-day
Salts, inorganic	17×10^{-3} lb/man-day
Organics, insoluble	6.5×10^{-3} lb/man-day

Air Condensate Water (3.8 lb/man-day basis)

Trace contamination

Feces (0.33 lb/man-day basis)

Solids 0.11 lb/man-day (wide spectrum of organics, bacteria, fats, acids, etc.)

FIGURE 11

References

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DISCUSSION

QUESTION: What do you mean by vapor hydrolysis? Are you concerned with the water vapor or liquid water.

DR. MALCOLM: The vapor pyrolysis system is used in conjunction with vacuum distillation, that is distillation at reduced pressure to avoid hydrolysis of the urea. In this process there may be some hydrolysis or ammonia produced. To eliminate the ammonia, the vapors, the distillation vapors, the water vapor and any ammonia that might have been hydrolyzed with the urea are passed through a heated catalyst. This is at an elevated temperature, oh, in the order of magnitude, say of 1200 C. if I remember correctly, and I may be wrong, but anyway it is in the report, and after this catalyst, the primary function is to oxidize the ammonia down to nitrogen and water. The heated vapors are then cooled with a regenerative heat exchanger. In other words, this thing trades heat from the incoming vapor to the outgoing vapor, so the term vapor pyrolysis is a sort of a short nomenclature for this vacuum distillation with pyrolitic oxidation of the hydrolized urea.

APPLICATIONS OF THE CONSTANT VOLUME HARD PRESSURE SUIT TO FUTURE SPACE PROGRAMS

Emil deGraeve

The first celestial object to be explored and exploited by man, as we all know, will be the one lying nearest at hand—earth's natural satellite—the moon. For the past two years the activities of this Working Group on Extraterrestrial Resources have been principally guided by the anticipation of establishment of manned bases and observatories on the surface of the moon. Projects of the magnitude envisioned by this Group can only succeed if supported by an unprecedented development of equipment, logistics, and individual skills. These developments obviously cannot result from on-site research and training because of the prohibitive costs and the extremely hazardous environment. First operations on the moon will have an all or nothing characteristic which makes it imperative that every step be rehearsed beforehand and every piece of equipment be exhaustively tested under conditions accurately simulating those which will be encountered. It is clear to everyone that new and revolutionary concepts must be fully investigated; that where these concepts are proven feasible and compatible with others in the state of the art, they must be optimally configured and incorporated with our systems designs; and that, finally, an adequate program of equipment testing and personnel training is absolutely essential to insure maximum probability of success of lunar operations and minimum loss of lives of trained space crews.

The first man to emerge from a lunar lander and literally set foot on the moon will undoubtedly perform an operation consisting of a series of well specified tasks, each of which he has already performed under simulated conditions many times on earth. All weaknesses in the equipment and in the logical formulation of the procedures to be followed will have been eliminated through reiterative trials and examinations. Furthermore, the consequences of various possible types of failures will have been analyzed. Emergency procedures will have been formulated for those that warrant such preparations.

On the first visit to the moon, it is possible that mere arrival at and departure from the surface may satisfy the initial objective and scope of the program. However, subsequent visits will represent a progressive series of encounters with the new environment. One possible chronology of events could include the following steps:

First, man emerges from his landing craft, plants insignia on the moon, gathers samples of lunar crust, and returns to his craft.

Second, man emerges from landing craft with data gathering and transmitting equipment; equipments are set up and made to operate; man returns to craft.

Third, lunar exploration sorties make seismic soundings of the moon.

Fourth, lunar tractor with driver rolls out of landing craft and makes excursions of various short distances over surface of the moon.

Fifth, group of men with lunar construction equipment makes sub-surface explorations.

Sixth, group of men undertakes construction of surface or underground inhabitable quarters and prepares for occupancy.

Seventh, lunar astronomical observatory is assembled and established as a permanent installation on or near the surface.

Eighth, a continuously growing supply of special equipment is ferried to the moon outpost and is placed in operation. The reliability of older equipment begins to diminish, requiring an increase in maintenance and repair activities.

Ninth, a launching pad is constructed and tested for a lunar launch to other planets of the system.

Tenth, geological studies are completed; mining operations begin; raw material processing begins; the first exploitation of extraterrestrial resources begins.

Some of these speculations will probably prove to be correct while others will not. Whereas the details of future space programs can, even now, only be hypothesized, the general trend of the overall effort can be more confidently stated: namely, a progression of more and more ambitious and complex undertakings to follow closely behind a progression of technical advances, and a continuation and extension of project developments will be required as each new task objective is defined.

One point appears to be uncontestable. Man himself will be the key element in the exploration and exploitation process; and from the time he

begins his explorations of the moon until the time he completely abandons, if ever, all such operations, there will be an unending series of developmental programs each culminating in hardware designed for operation under lunar and, later other, planetary conditions.

The vastness and complexity of the program ahead of us can only barely be grasped by considering the amount of capital and numbers of people involved. It appears that about 5% of the gross national product of the United States alone is the commitment that we have made.

A few have questioned the wisdom of this commitment in terms of alternative challenges open to us. There are many others who accept the commitment but question the level of effort being applied especially in the time scale set for accomplishment. These arguments may never be resolved to everyone's satisfaction, but one thing is certain: if the commitment is to be justified at any level of effort and in any time span, man will have to demonstrate his own effectiveness in the system he is devising to accomplish the grand objective.

Man's effectiveness can be approached and measured from many points of view but, fundamentally, all of these resolve down to his two essential attributes of form: his brains and his brawn. In man's natural environment it has been his wit that has enabled him to prevail over and exploit all other forms of life as well as the natural resources of the earth. Indeed, man's wit has brought him to the point where he is ready and apparently able personally to exploit the rest of his universe. From the earliest time that he began his earthly conquests until the industrial revolution and the new age of automation, man's muscles served him well and importantly. But, ever increasingly since the beginning of the industrial revolution, brawn has played a lesser and lesser role, except for recreation, in the success story of man's effectiveness in coping with his earthly environment.

Thus, man's thinking may be seriously distorted—distorted by the fact that his activities, during virtually the entire history of the race, have been confined to a thin film of air adhering to a gravitating planet, whereas, by far the greater part of the universe is occupied by a high vacuum ranging from 10^{-16} mm Hg in intergalactic space to about 10^{-11} mm Hg in interplanetary space near the earth. It is evident that the enormously high pressure of 760 mm Hg existing at the surface of the earth is far from being "normal" and actually constitutes a very exceptional environment.

To say that such considerations are no longer academic, in the light of events in this decade, is almost an anachronism. Airlessness and weightlessness, radiation and particle impingement are conditions which require us to learn a whole new way of life. It is a rather startling observation, in the light of our long historical development and the projection of what seem

to be well established trends, to note that man's effectiveness in the world beyond this thin veil of air may well depend more on his ability to use his brawn than his brain.

Consider this peradventure: a decade of effort and, in almost every one of those years, a significant percentage of America's gross national product have been invested into transporting man to the moon so that he may perform that first act of emerging from his lunar lander, plant the American insignia on the moon, gather samples of lunar material and return to his vehicle. But upon emerging from his craft he finds he can't bend over! Or, if he falls, he can't pick himself up—light as he may feel! Or, if he can do these things, the decrements in efficiency with which he can perform such acts are so high that he becomes completely exhausted in a small fraction of the mission time alloted for him to be away from his vehicle. Or, instead of one-man accomplishment of an assigned task it is found that four men are required. The inferences to be drawn from these considerations, to some, are appalling.

Streimer, et al[1] have recently published the results of a study which investigated the effects of pressurized suits on the output characteristics of workers performing simple tasks in normal and reduced-traction environments. While the data admittedly are not definitive nor the findings conclusive, the results make it abundantly clear that "the energy requirements for work in the suits tested are so gross that a demand for meaningful quantities of work may be wishful thinking". These investigators were startled by evidence that showed losses of efficiency measured by increased exertion values of more than 350 percent, excess heat production on the order of 1000 to 1200 BTU per hour, and severely curtailed productivity. In calling for an "agonizing reappraisal of this aspect of the manned space program", they concluded:

"If suited operator efficiency continues to be impaired to the extent found in these investigations only three alternatives remain open to system planners: more men, or more time per unit work load must be provided, or the work load requirements must be drastically reduced. The first two alternatives may be inadmissible for sundry reasons while the third may negate the productivity of the man to an extent that makes some aspects of the manned space program suspect".

Fortunately, the situation with space suits is not all as debilitating as it may seem. The solution to many, if not most, of the problems uncovered by Streimer and his associates is to be found in a manifestation of the constant-volume prinicple of flexible pressure vessel design. This principle is embodied in what we call the 'rigid, articulated, anthropomorphic pressure assembly', sometimes referred to as the "hard" suit, currently being investigated and evaluated by the National Aeronautics and Space Administration's Manned Spacecraft Center. NASA's interest grew out of a

development at Litton Industries first supported by the Air Force Office of Scientific Research as far back as 1955. At that time, Siegfried Hansen[2], then technical director of Litton's Research Laboratory, began his work on the development of an arm and glove section. He reasoned that, if volume could at all times be held constant while under pressures of 5 psi over ambient or higher, such articulated sections would provide minimum flexure torque and, therefore, maximum mobility. Success with the arm would mean that a whole suit could be designed in accordance with the constant volume principle.

Hansen's initial motivation was to place an experimenter inside a large vacuum cylinder, wherein it was expected that a researcher could greatly broaden his opportunity to engage in advanced vacuum tube development. Aircraft pressure suits were out of the question if a hard vacuum (10^{-6} mm Hg) was to be maintained in the test chamber.

Neither Hansen nor the Directorate of Advanced Studies of AFOSR neglected the obvious implications of success for space suit applications, even though the word "space", until October 1957, was a sort of hushed curiosity in the national lexicon.

Hansen considered the problem of the tensile loads on the suit and the equally important problem of internal suit pressure as it leads to a source of traction stresses to which the suited man is subjected. A few illustrative examples of the tensile loads considered, at an internal pressure of 10 psi over ambient, are as follows:

Finger	8 lbs.	Leg	330 lbs.
Wrist	110 lbs.	Helmet	785 lbs.
Arm	280 lbs.	Torso	1,560 lbs.

In the movable elements of the suit these forces must be balanced with extreme care to avoid the generation of overpowering torques on the hands, arms and legs of the wearer.

It was evident to Hansen that, if he were to design a suit for 10 psi above ambient the limb extremeties had to be designed with flexible restraining devices which were balanced against internal forces to an accuracy of better than 1 percent (See Appendix A). For only by this means could the debilitating torque effects be avoided. Pneumatic forces have a spring-like characteristic in that they tend to produce a force proportional to deflection, but they can also produce either a straightening or buckling effect depending on the sign of the coefficient.

Another type of force, which Hansen had to consider, and which is related to mechanical efficiency was, of course, the friction force whose

characteristic is to oppose motion regardless of direction. While not as tiring as a continually maintained spring force, friction is objectionable in that it interferes with dexterity of manipulation and is also related to wear and hence to durability of the suit — a not inconsequential problem in a hard vacuum.

It was clear from the outset that a constant volume pressure suit could have very little in common — from a design standpoint — with the altitude or "soft" suit as it was then known in the state of the art.

The development proceeded under far-sighted Air Force sponsorship even though at that time (1956) it was justified only as a "remote manned manipulator station for vacuum applications." The suit was successfully demonstrated by June, 1957. In October of the same year the Sputnik achievement immediately called attention to the suit for space applications. One would like to say fortunately, but unfortunately, the suit was ahead of its time.

We know that the Mercury project did not require a man to exit his vehicle in free space. Even in Gemini, while he will be exposed briefly he will perform no work functions as such in the space environment. It has been only with the advent of Apollo and, more pertinently, post Apollo landing missions that the so-called "hard suit" has come into its own.

Development work on the suit was modestly maintained by Litton Industries from 1958 to 1963. In 1963 NASA's Manned Spacecraft Center recognized the possibility of utilizing the constant-volume principle in suits intended for use primarily in extravehicular and lunar surface missions. Today the prototype of such a suit is a reality (as you will see in a film clip which will be shown in a moment). Additional development work is needed and is under way. Of one thing we can now be certain: there need no longer be any real concern that man will be able, with complete effectiveness, to take that first fateful step in the long, perhaps never ending, series of steps leading to his exploration of extraterrestrial resources.

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APPENDIX A

A NOTE ON THE NECESSITY FOR A SPACE SUIT OF CONSTANT-VOLUME DESIGN

The purpose of this note is to show, by illustrative example, the degree to which a space suit must adhere to the constant-volume principle of design. A departure of as little as 1% leads to a condition where fundamental body movements, such as walking, require the expenditure of excessive quantities of metabolic energy.

Suppose a suit is operated at a pressure, P, above ambient, and suppose that a certain movement leads to a change in suit volume equal to δV. The mechanical energy required to accomplish this movement is equal to $P\delta V$. The forces involved are pneumatic and therefore have a spring-like character. In spite of this, the energy cannot be recovered by the metabolic system of the body; so $P\delta V$ represents a real expenditure of metabolic energy. In addition, the muscles of the body must hold against the forces so even more metabolic energy is required. The total energy required can be expressed as $P\delta V/\eta$, where η is the net efficiency of the body. Experiments show that η is typically lower than 25%.

If the operation in question is repeated N times per second, and if the suit pressure, P, is expressed in psi, and if the suit volume, V, is 18 cubic-feet, then it can be shown that metabolic energy must be expended at a rate, W, where:

$$W\ (\mathrm{BTU/hr}) = 12{,}000\ \frac{PN}{\eta}\left(\frac{\delta V}{V}\right)$$

By way of example we consider a man walking at about 1.5 miles per hour. Then $N \approx 1$ step/sec. We also take $\eta = 0.25$. Then

$$W = 48{,}000\ P\left(\frac{\delta V}{V}\right)$$

The rate of energy expenditure predicted by the above formula will be an addition to that normally required in walking. From experience we learn that W should not exceed 1000 BTU/hr, so $\delta V/V$ must satisfy the following condition:

$$\frac{\delta V}{V} \geq \frac{1}{48\,P}$$

APPENDIX A
(continued)

This equation yields the conservative results shown in the table below:

TABLE I

Suit Operating Pressure (psi)	Maximum Allowable Volume Variation (%)
3.5	0.60
5.0	0.41
7.5	0.28
10.0	0.21
14.5	0.14

At an operating pressure of 3.5 psi the volume change occasioned by walking should not exceed 0.6%. Even stricter adherence to the constant-volume principle is required as the suit pressure is raised.

A. S. Penfold

DISCUSSION

QUESTION: Can he get up if he falls down?

ANSWER: In this suit, no. Present designs, I cannot go into detail on. As a matter of fact, we feel it undesirable to attempt such an experiment in a suit not specifically designed at the time for that capability. As a matter of fact, kneeling would be difficult. Of course we could provide the sit, stand, kneel, lay down and pick yourself up capabilities.

QUESTION: Have you considered a soft suit.

ANSWER: It is an interesting thought. We examined it about ten years ago, and rejected it. Our major reasons for rejecting it were we had to maintain our hard vacuum, and any kind of a soft suit would leak beyond tolerable limits, to maintain the vacuum.

This suit on delivery leaked at 52 cc for a minute. Leak rate for the present version, is under 25 standard cc per minute, and the present soft suits in their best configuration on delivery are leaking at, I think 200 standard cc per minute, and after two or three donnings and doffings were up to 400 cc per minute. We have even heard comments of some people that they even leak on the order of liters per minute, after several donnings and doffings. Whereas, after 12 donnings and doffings, and 30 days or more of use, the leak rate for our hard suit did not rise by one standard cc.

MR. GREEN: This is a general question. There appears to be a lot of work to be done by geologists and astronauts in which they are going to have to carry cameras and various tools, hammers; what kind of liaison do you have with people who are directing missions? I would like to see people handle a camera. How do you communicate?

MR. DE GRAEVE: Well, we made one attempt to communicate with the Scientific Community a few months ago through Brother David, through Rockets Magazine, and shortly after that the program got classified, so I don't know what ability we have to communicate, except through NASA channels. I suppose if you have problems like that and are now aware there is such a suit and it has possibilities for you, you merely contact NASA at the Advanced Spacecraft Center and say you have an interest in the suit, and need to know cases coming up, and discuss it.

QUESTION: I had a Vickery suit on and did some chores, and I found out I could do one-third of what I could -- I can't lift my knee. There is a field for geological exploration.

MR. DE GRAEVE
ANSWER: Yes, there is. However, this is not thought of as a suit for vehicular operations. This is only thought of by NASA so far as an extra vehicular and lunar surface suit. So you must keep in mind that suits used in vehicles are really emergency pressure suits, and they have always been that way. They provide immediate protection for

the man on decrease of pressure. So not very much thinking has gone on in this direction, till recently, and that is about as far as I can comment on that point.

STATEMENT: I have a limited ability to comment on other suits, though I will say this, and these are simple facts: the suits are soft, they tend to take the shape that they are sewn into, with all the convolutes you may care to introduce into them, they will assume some normal position and it is usually a position that is designed into them, that we feel is most common for the man to have, for all the mission circumstances that they expect him to be wearing the suit in.

It is a fact that closures for these suits are basically zipper designs, and a zipper on a pressurized gas bag, it seems to us is a very poor seal, and perhaps accounts for the major portion of the leak that does occur in this soft suit. Some people have commented that the hard suit is rather bulky. This is accounted for for two reasons, in one case, we tended to overdesign the suit in the first place, in order to save time and money and avoided miniturization and extensive investigations, merely to prove the constant volume principal to the satisfaction of NASA, and as a result you see a very heavy main body seal and rotary seals, when you consider the weight of the suit.

The other factor accounting for the bulk of our suit is that there are other, shall we say componentry envisioned for the future that had to do with thermal control, environmental control systems, life support, and so on. I might add this, this is a long extenuation type answer to your questions which I want to get back to in a moment, is a Litton concept and I must emphasize here that it is not a NASA concept at the moment. Although we have been discussing it with them, but they are not nearly as convinced as we are that we can provide a distributive thermal control system for this suit fully integrated into the hard suit by making the suit itself to be a heat exchanger and completely eliminating the weighty back pack that the man would otherwise have to carry around for thermal control.

So those are the reasons why our suit appears bulky, but when you take a soft suit which looks very unbulky in an unpressurized state, it is after all a restraint device, on the same principle that the corset is, and as you try more and more to provide mobility to these suits under pressurized conditions, you find you have to add more and more convolute, ribs, to them, and the result is that they get bulkier and bulkier until finally they look just as bulky if not more bulky than this suit when they are under pressure.

So I would say in answer to your question, do we think the state of the art in soft suits has reached its zenith, it may, indeed have passed its peak. There may be very little potential for increase in the use of these suits as workers' garments in space. And that the state of the art in hard suits which began ten years ago is now just picking up some momentum. Perhaps the two will cross. Perhaps they will each serve their purpose, soft suits certainly can always be useful as an emergency pressure suit in systems or aircraft or vehicles where recovery aboard is very swift, but I would be one who would be very uncomfortable asking anyone to wear such a suit as an emergency protective device on any long recovery program.

QUESTION: Morton, G.E. I had an opportunity to speak to Scott Carpenter and Chuck Yeager, and the three Russian people who were over, and the Russians--Scott Carpenter and Chuck Yeager all maintain that as far as they were concerned the biggest engineering bottleneck as of right now is the pressure suit. The Russians, in their last three manned flights, their men did not wear pressure suits during the entire flight.

ANSWER: And more than that, they revealed this for the first time at that meeting, all seven of their flights have been at full atmosphere, common air.

I would like to just comment on a question that was asked much earlier about who is giving through to all the transition problems going from 7 psi to 5 psi to 3.5 psi, in the total system. It is our contention, of course, that we would have single gas pressures. Now that may be and perhaps should be a mixed gas in constituent atmosphere. The one that seems to be getting the most sympathetic attention these days is about 7 psi of 50 percent oxygen and 50 percent nitrogen. If we could all settle on this once and for all, it would grossly simplify I think, the systems designers problems. But the Navy has always been at one end of this argument. In talking about full atmosphere, Dr. Marr never wanted to send anyone up in gondolas except at full atmosphere, and he would agree with the Russians, or they would agree with him. The Air Force, of course, has always tried to go as low as they could, because they put considerations in their optimizing designs of aircraft, and all that NASA appears to have done is to have taken some middle ground here and so the controversy still rages about what is the best practice; what is the best gas composition.

Suits have always been a limiting factor in what one could consider in terms of higher pressure and even mixed gas requirement. We don't think the control problem is that severe. Then certainly suits like this ought to influence people to think more and more, at least about 7 psi.

DR. GILLESPIE: What is the material of the articulated joints, elbow type joints? Is that metal or some sort of fabric?

ANSWER: I can tell you that what you saw here is aluminum, 40 mils. 60 60.

DR. GILLESPIE: I ask that because of my concern with possible corrosive nature of the atmosphere of Mars when we get there, and I would like to see our lunar suit be useful for that purpose, without change.

ANSWER: We are at work on material selection for the operation prototype of this suit, and your question is a very good one. I cannot really tell you what we are at work on now without permission from NASA, or what they would be willing to release.

DR. MORTON: General Electric. What is he going to do about the heat loss. Let's say someone has to pick up a tool that has been exposed to the lunar surface for an hour, and you pick it up with that metal glove. How are you going to protect the man's hand? from the temperature?

ANSWER: First of all, this was a non-metal glove which you saw. There are metal parts to the glove. These heat transfer problems are also very much a part of the considerations of the designers now.

I think I ought to say this in defense of soft suits; the best glove design we have seen has not been our own, but they have just recently been exposed to us, at least, and in the latex suit and the Hamilton Standard suit and in De Parkway's Gemini suit, they are excellent, and we may not continue our own exploration of that problem.

DR. EDSON: I would like to make a few remarks in addition to those which have been made about this pressure suit.

We have, in the Office of Research and Technology, for a little over a year now a coordinating group on winter technology which has been looking at the problem of technical readiness for lunar operations. Gradually in the course of those months we became aware of the importance of the suit, and what we are trying to do. In fact, when we came to realize that the capability for human maintenance and repair equipment is so great and the times necessary merely for the test of equipment to be operated for long times unmaintained is so high along with the other costs and difficulties that if the space program is to be an adequate tool of national policy and responsive, technically, to national policy with a sort of decay time or adaptation time of less than ten or 15 years, we must have a good work suit. This makes the difference, between the utility of a space program as an instrument of national policy or for any other purpose, and the virtual uselessness of manned astronautics. We learned this slowly in detail, the hard way and we have ever since then been attempting to point this out to others. We sent a memo to Jim Webb and said that it was just this way, if the President wants the Space Program to be an American tool of policy, we have got to have a good work suit. I would like to add, then, this note of confirmation to the spirit of what has been going on here from the standpoint I mentioned, it doesn't make any difference whether it is a hard suit, soft suit or some kind of a suit nobody has thought of yet, but by 1970 we had better have a suit in which a man can work freely in space environment.

APPENDICES

APPENDIX A

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18 - 20 NOVEMBER 1964

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APPENDIX B

TECHNICAL PAPERS PRESENTED AT THE WORKING GROUP ON EXTRATERRESTRIAL RESOURCES ANNUAL MEETING 18-20 NOVEMBER 1964

Contents;

Environment and Resources ~~Subgroup Report~~	Salisbury
Logistics Requirements Subgroup Report	Henderson
Mining and Processing Subgroup Report	Hall
and Biotechnology Subgroup Report	Craven

ENVIRONMENT & RESOURCES SUBGROUP

Infrared Emittance & Reflectance Spectra of Rough and Powered Rock Surfaces	Lyons
Determination of Compositional Differences on the Lunar Surface using Ground-based Infrared Spectroscopy	Salisbury
Hypervelocity Impacts (Film by Gault)	Salisbury
The Surface of Mars	Sinton

MINING & PROCESSING SUBGROUP

Indentification of possible Lunar Resources	Green
Early Mission Experiments and Lunar Resources Exploration	Van Lopik
Serpentine as a Source of Water on the Moon	Weber
Removal of Oxygen from Oxides by Fused Salt Electrolysis (not presented)	Herold
Stability-Metestability Relationships of Hydrous Minerals (not presented)	Weber

MINING & PROCESSING SUBGROUP (Continued)

Arnold Engineering and Development Center Lubrication Program	Peters
A Preliminary System Concept for Extraterrestrial Mining and Processing	Hayward
The Application of Surface Mobility to Lunar Mining	Mitcham

LOGISTICS REQUIREMENTS SUBGROUP

Feasibility of Liquid Hydrogen Production on the Lunar Surface	Glaser
Soviet Lunar Construction Potential	Henderson & Mitcham
Requirements for on-site Manufacture of Propellant Oxygen from Lunar Raw Materials	Rosenberg
Some Uses for Planetoid Resources	Cole
Committee on Logistics Analysis (Originally part of Henderson's subgroup report)	Paul

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The Ecological Complex in Extraterrestrial Bases	Dole
Space Vehicle Atmosphere Control Systems, State-of-the-art Summary	Thompson
Waste Water Recovery in Extraterrestrial Environments	Malcolm
Applications of the Constant Volume Hard Pressure Suit to Future Space Programs	de Graeve